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Tang

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(54) **TWO-DIMENSIONAL, ANTI-SCATTER GRID AND COLLIMATOR DESIGNS, AND ITS MOTION, FABRICATION AND ASSEMBLY**

(75) Inventor: **Cha-Mei Tang**, Potomac, MD (US)

(73) Assignee: **Creatv Microtech, Inc.**, Potomac, MD (US)

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(21) Appl. No.: **09/459,597**

(22) Filed: **Dec. 13, 1999**

Related U.S. Application Data

(63) Continuation-in-part of application No. 09/373,972, filed on Aug. 16, 1999, now abandoned, which is a continuation of application No. 08/879,258, filed on Jun. 19, 1997, now Pat. No. 5,949,850.

(51) **Int. Cl.**[7] **G21K 1/00**

(52) **U.S. Cl.** **378/154**

(58) **Field of Search** 378/154, 155

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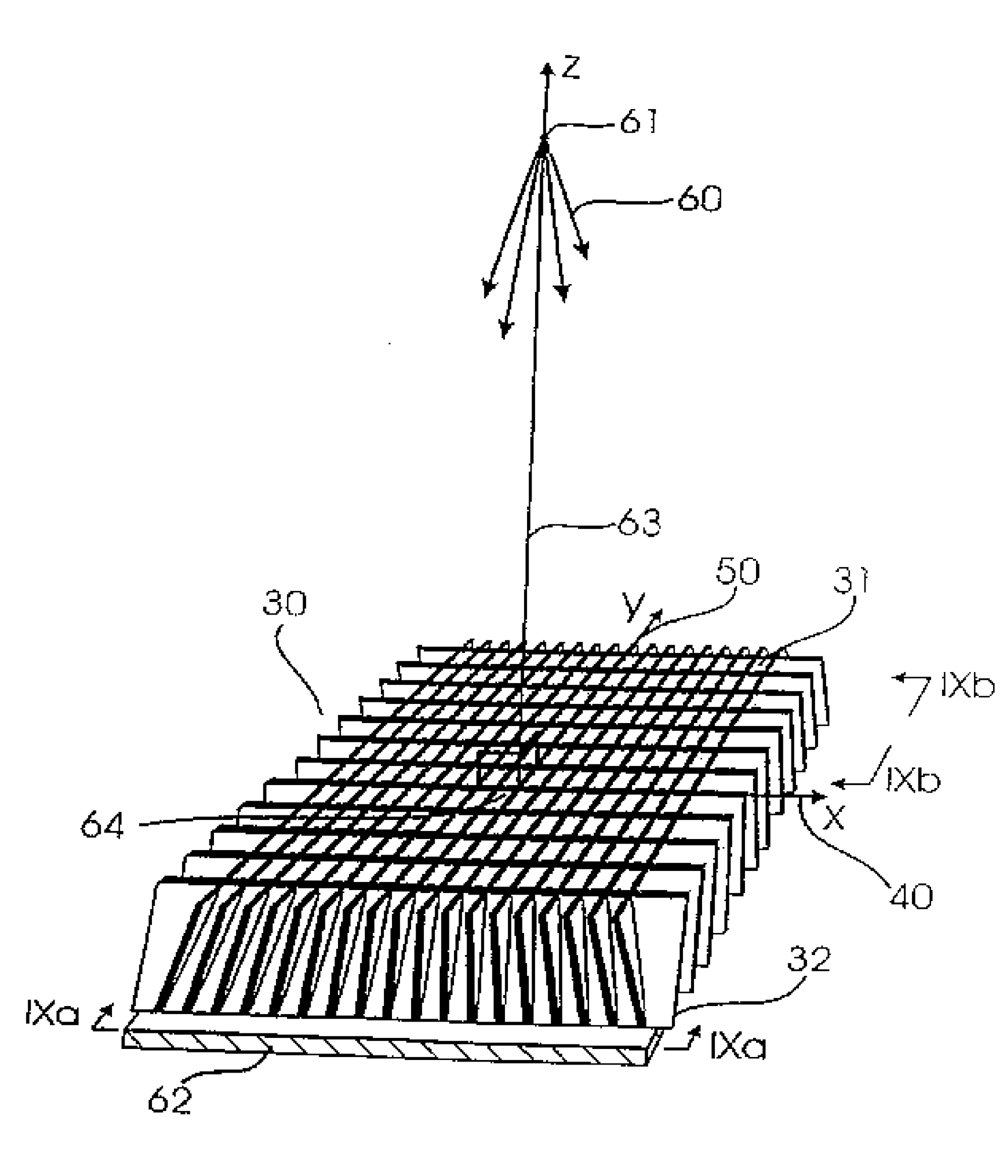
Primary Examiner—Craig E. Church
(74) *Attorney, Agent, or Firm*—Roylance, Abrams, Berdo and Goodman, LLP

(57) **ABSTRACT**

A grid, for use with electromagnetic energy emitting devices, includes at least metal layer, which is formed by electroplating. The metal layer includes top and bottom surfaces, and a plurality of solid integrated walls. Each of the solid integrated walls extends from the top to bottom surface and having a plurality of side surfaces. The side surfaces of the solid integrated walls are arranged to define a plurality of openings extending entirely through the layer. All of the walls can extend at 90° with respect to the top and bottom surfaces, or alternatively, some of the walls can extend at an angle other than 90° with respect to the top and bottom surfaces, such that the directions in which the walls extend all converge at a point in space at a predetermined distance from the front surface of the at least one layer. At least some of the walls also can include projections extending into the respective openings formed by the walls.

8 Claims, 38 Drawing Sheets



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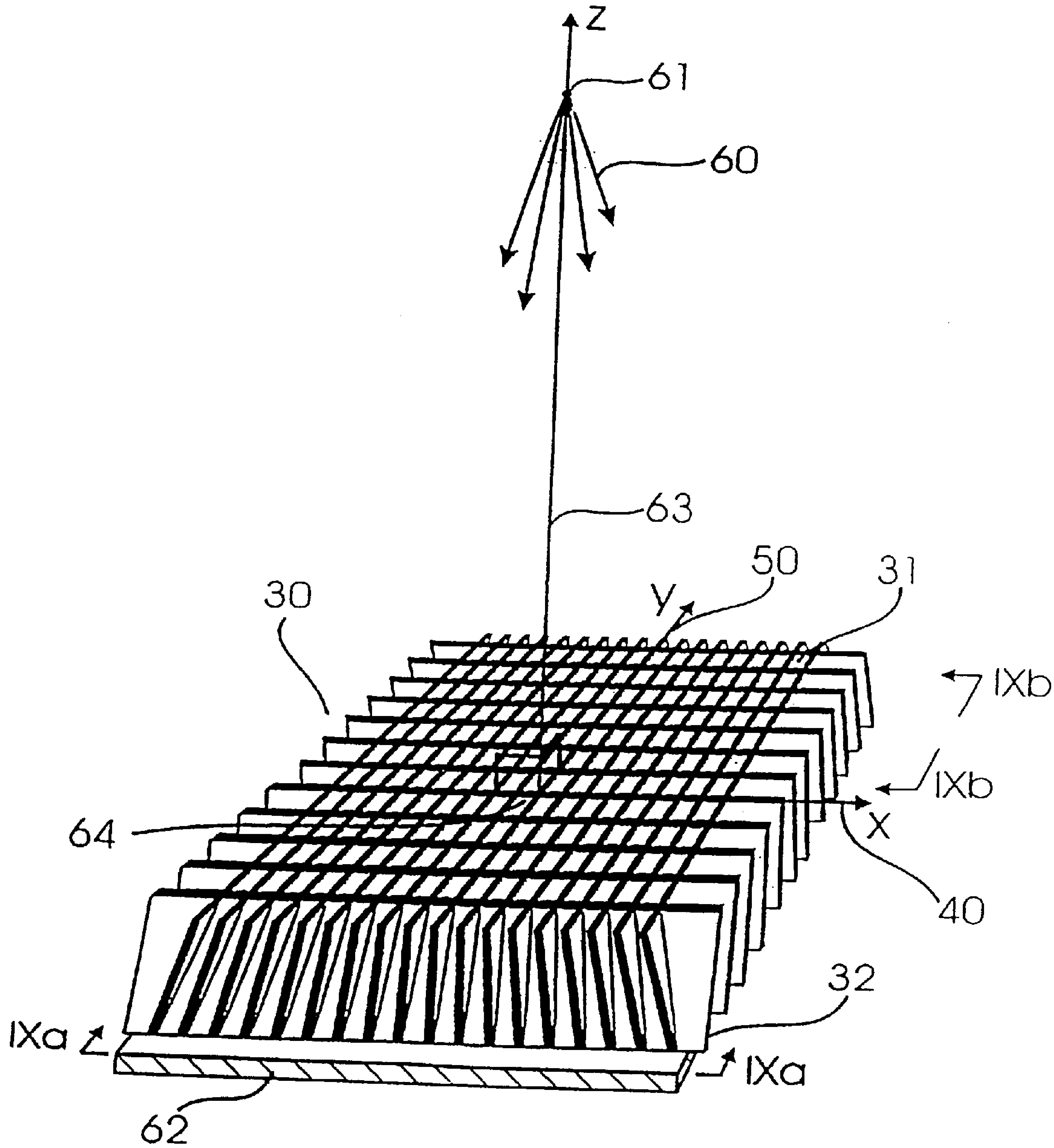


Fig. 1

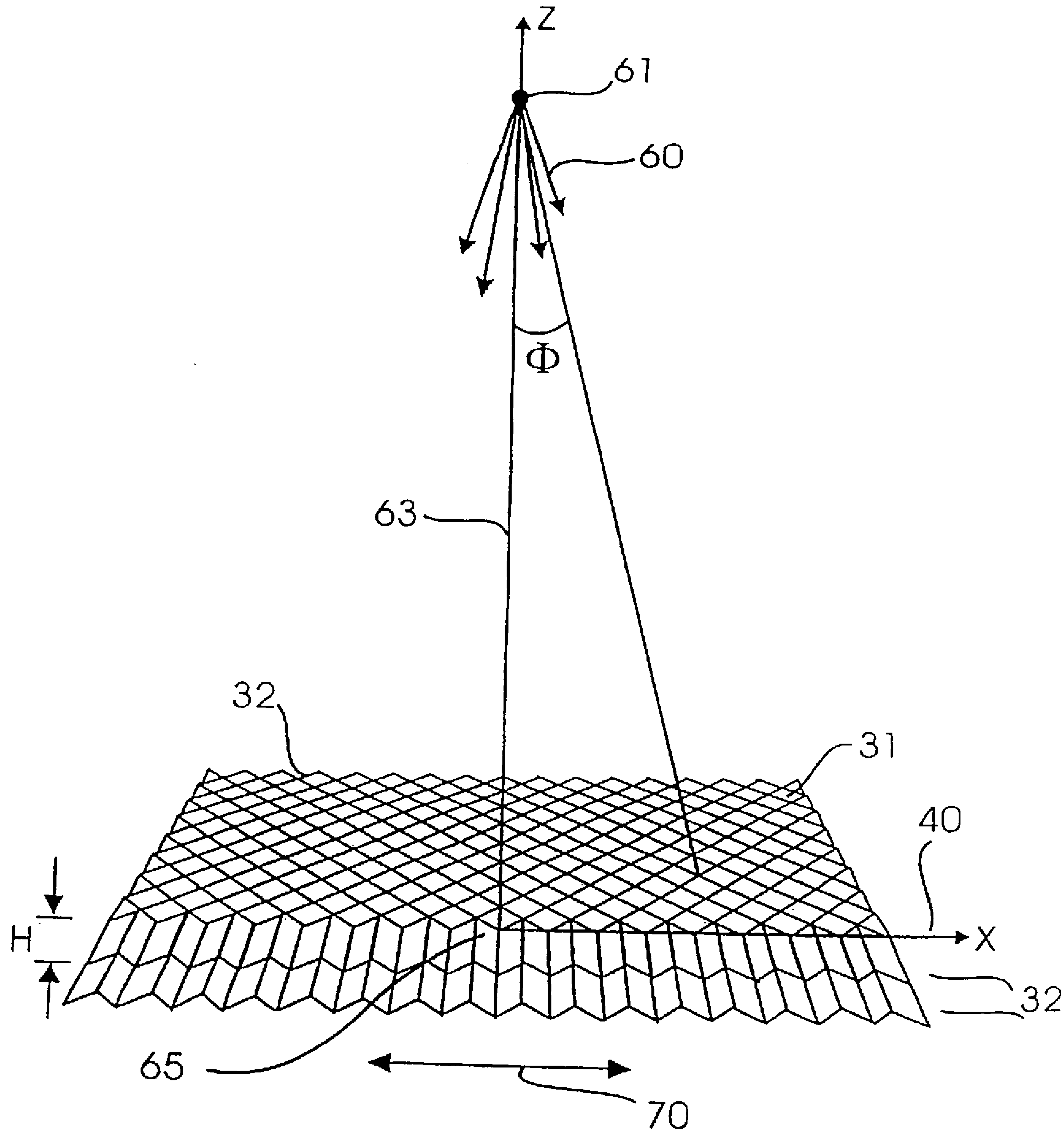


Fig. 2a

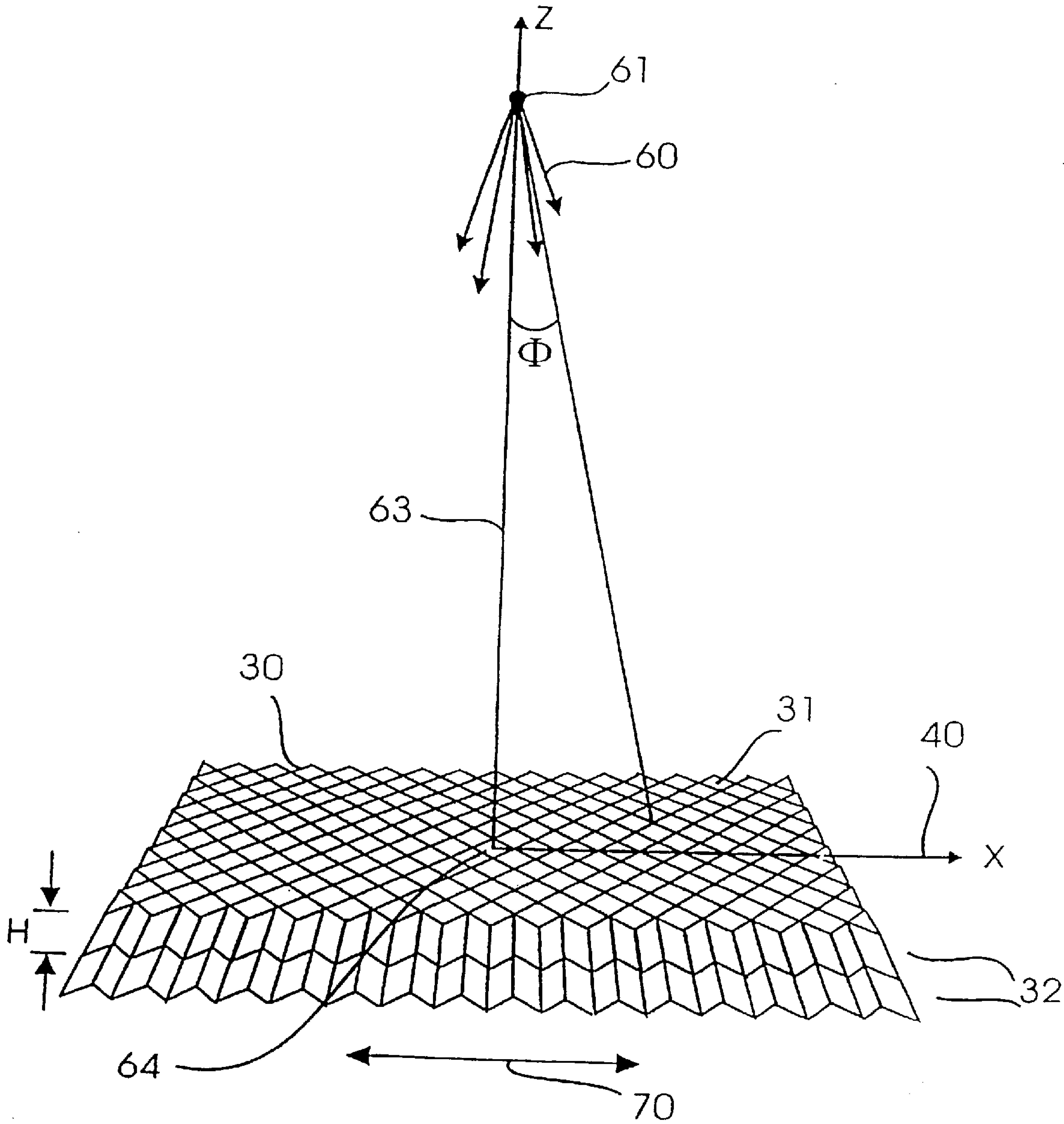


Fig. 2b

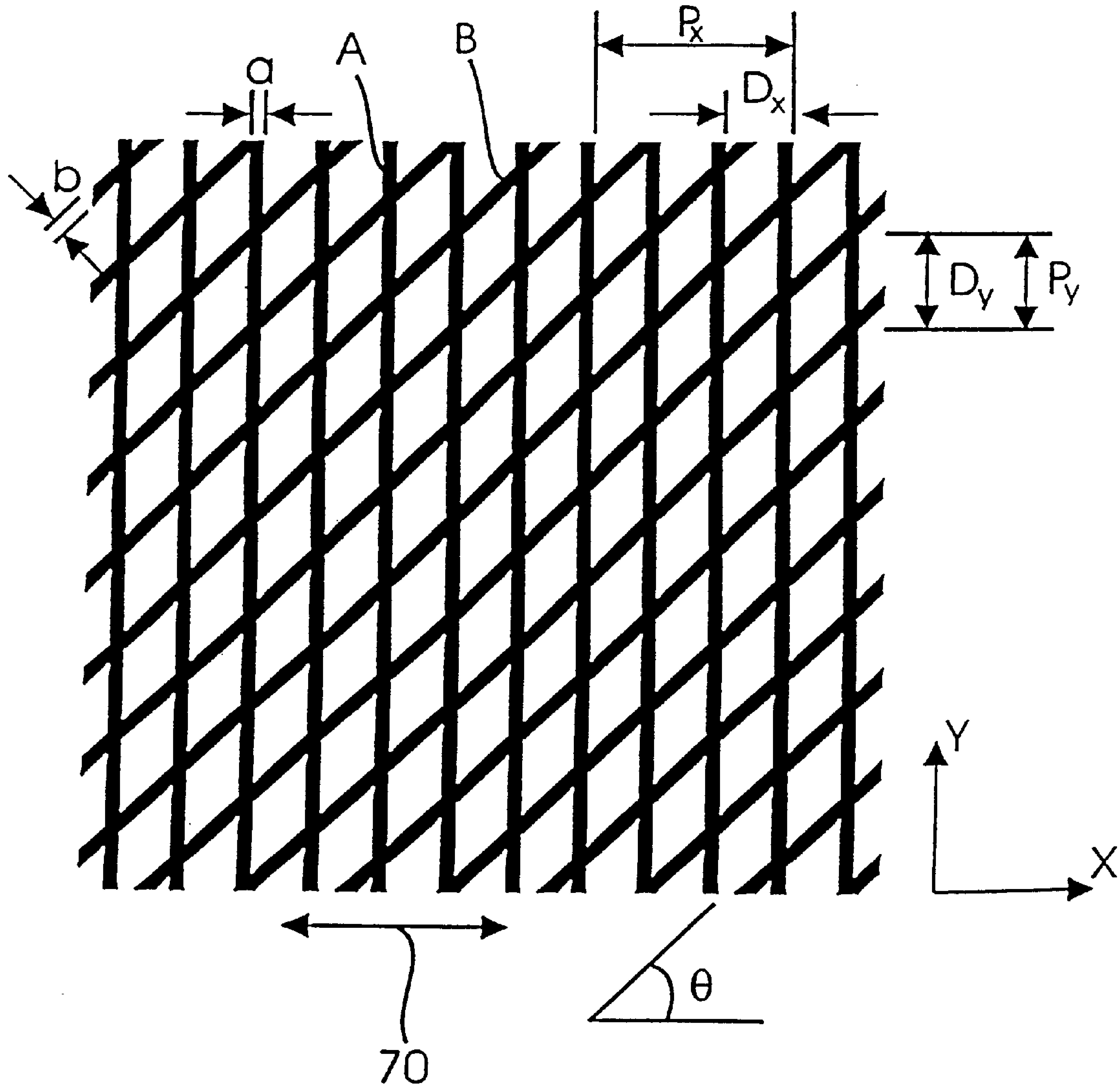
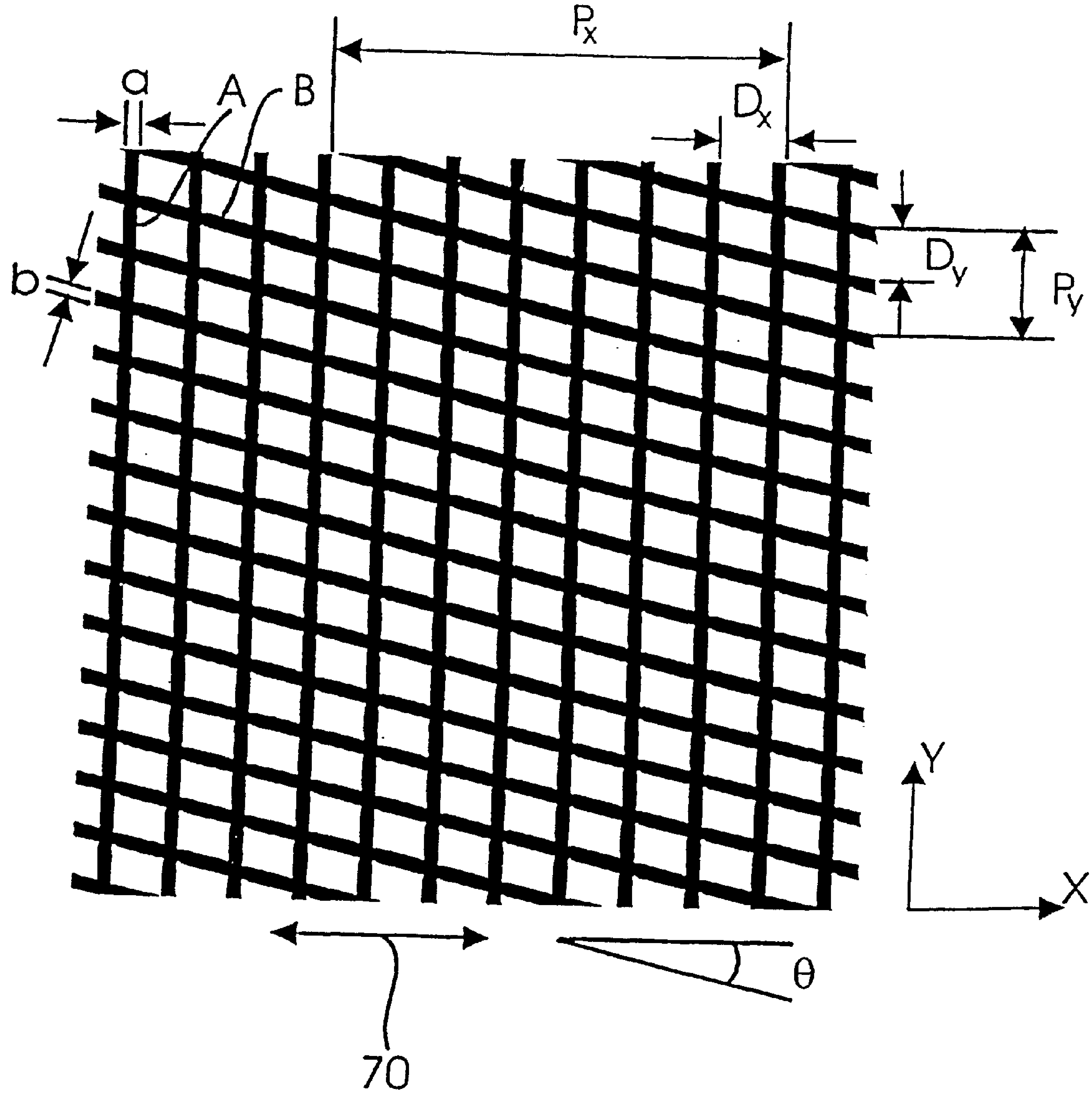


Fig. 3



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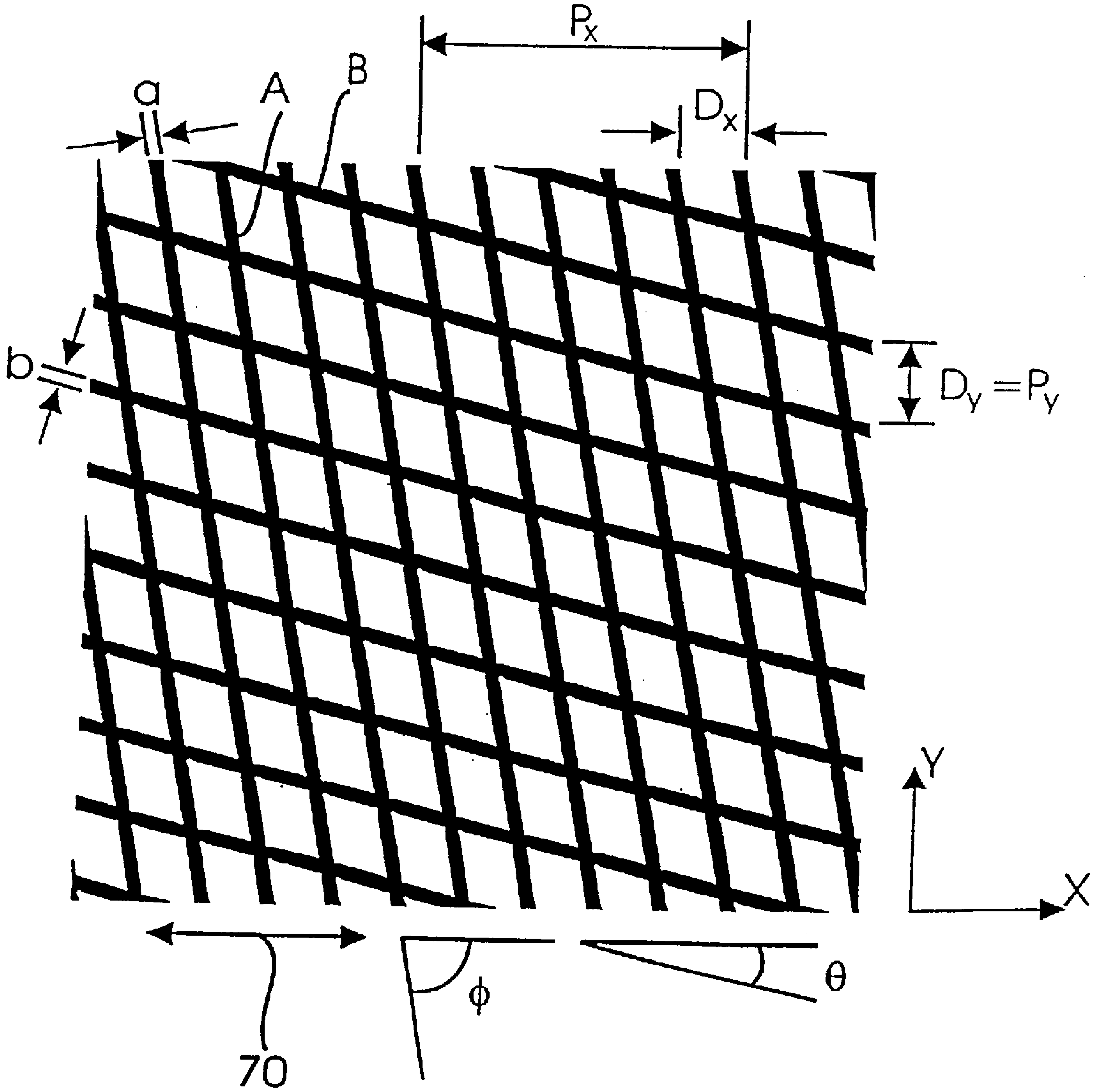

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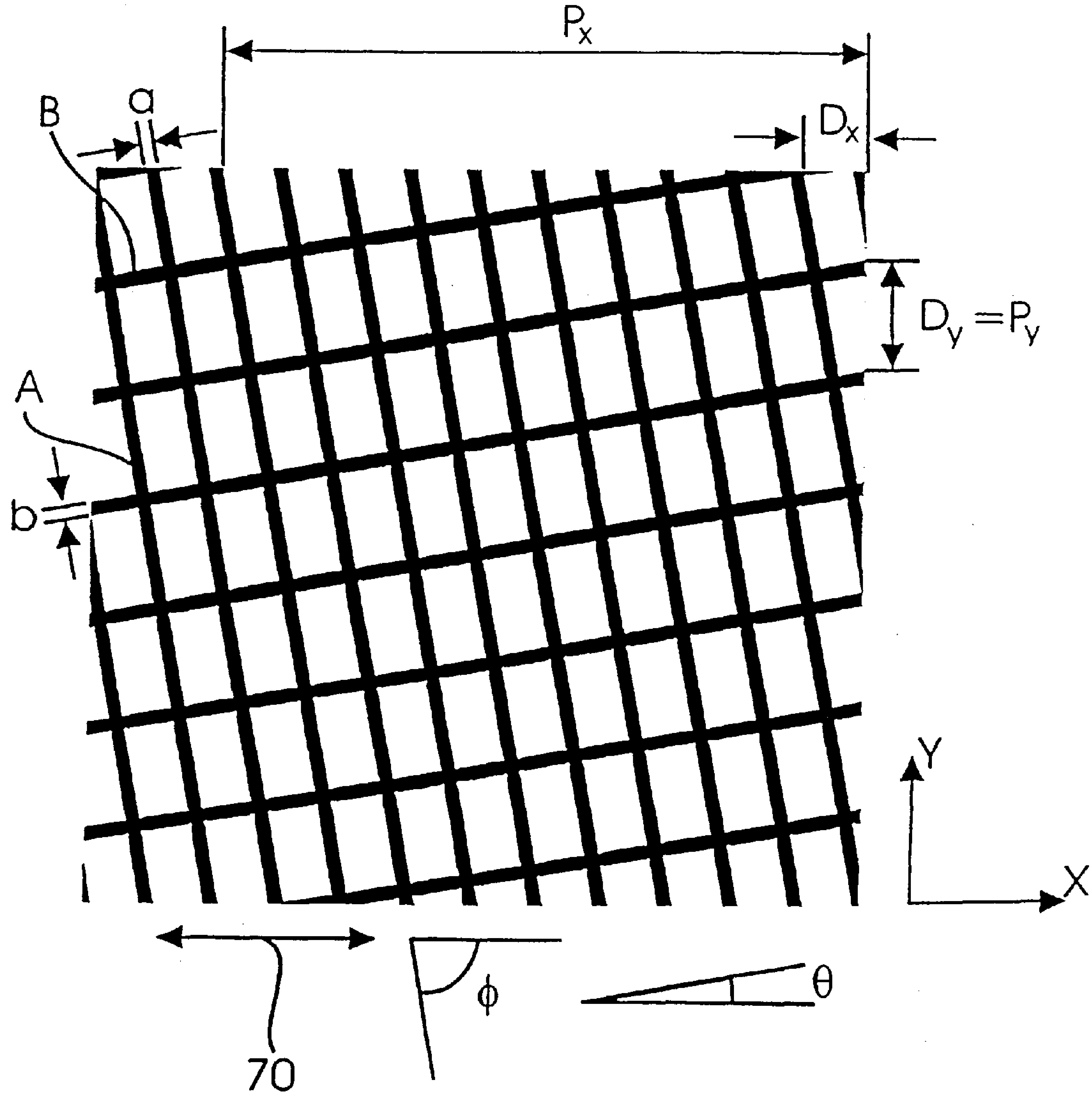

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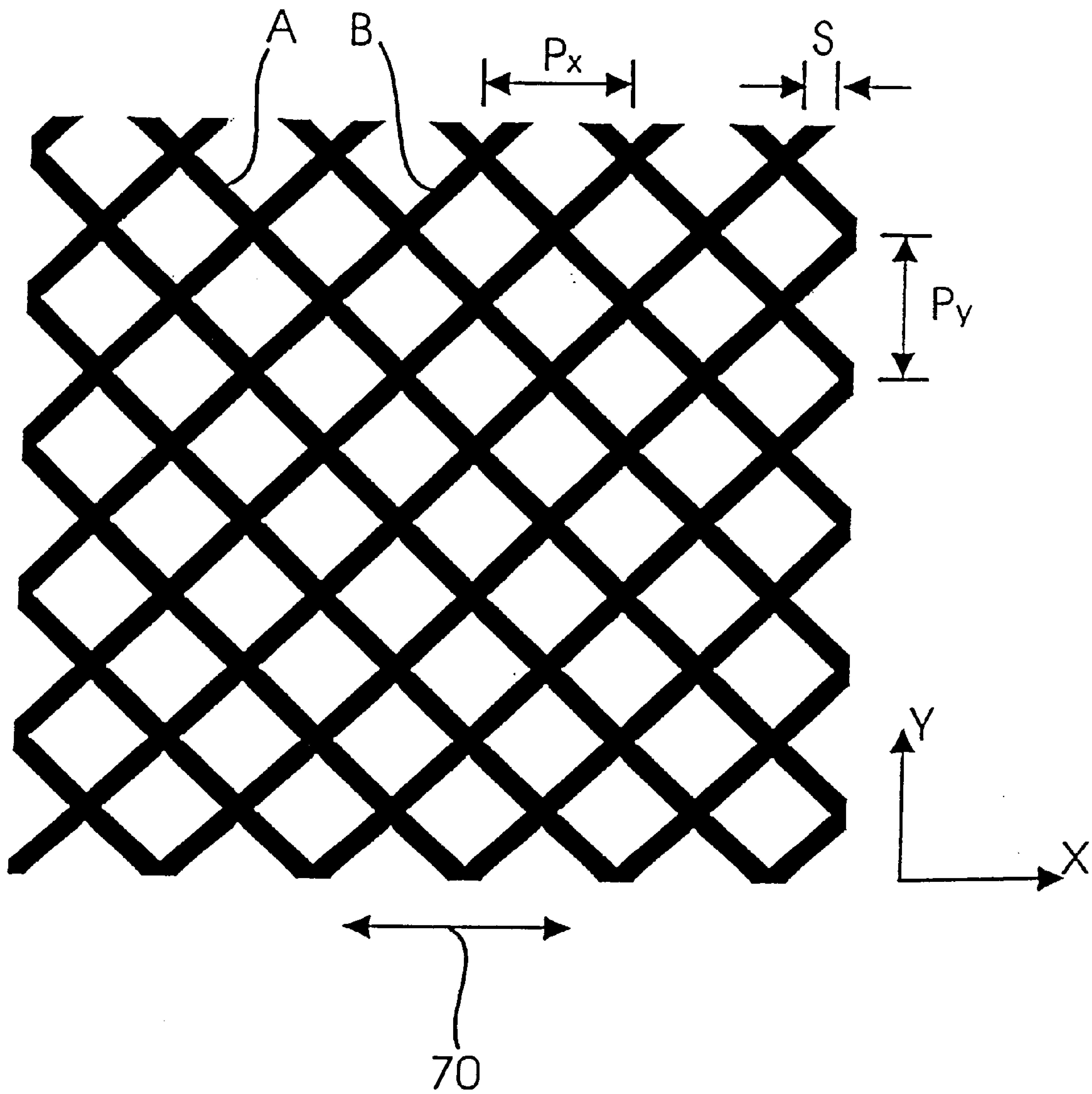

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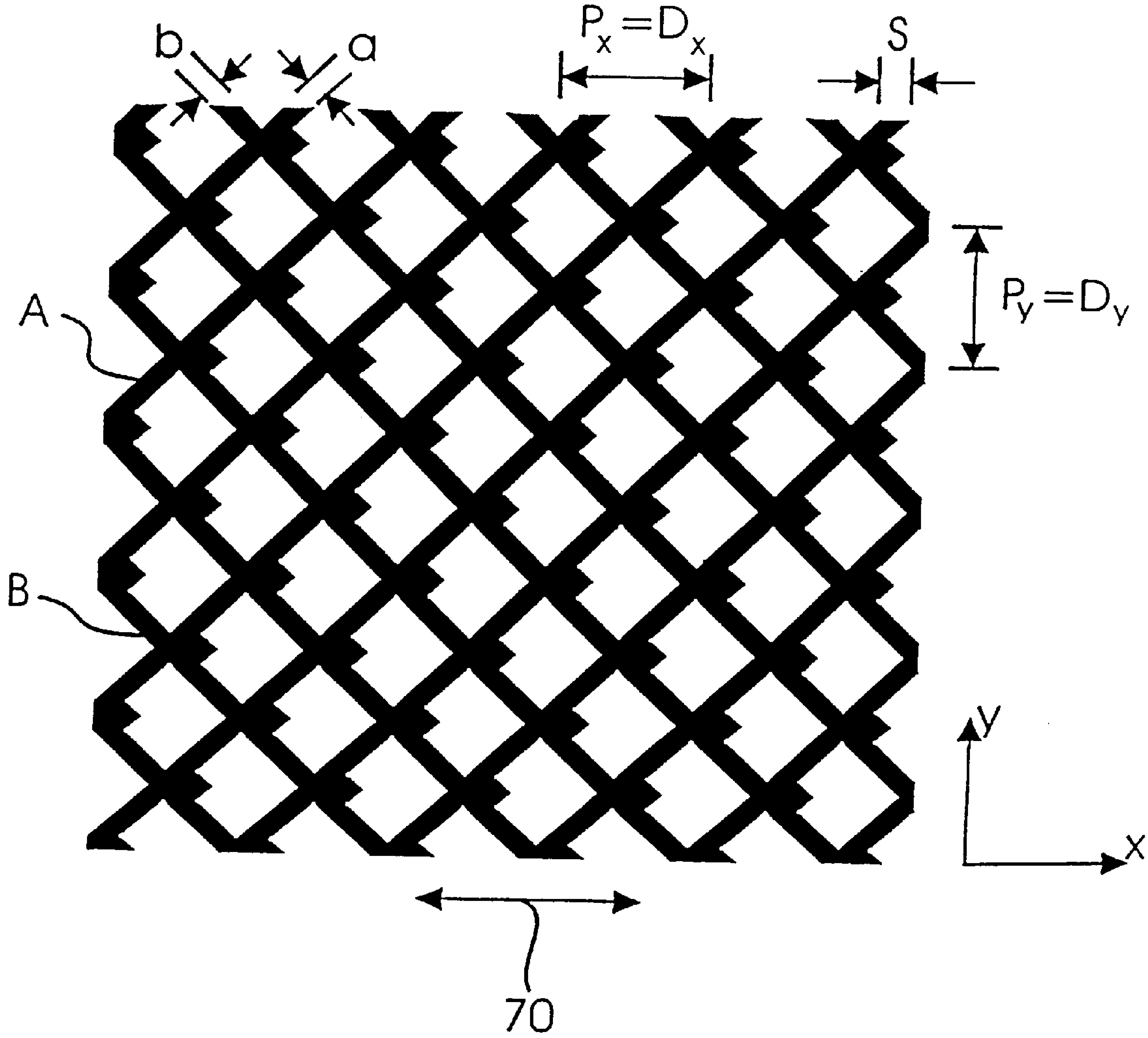

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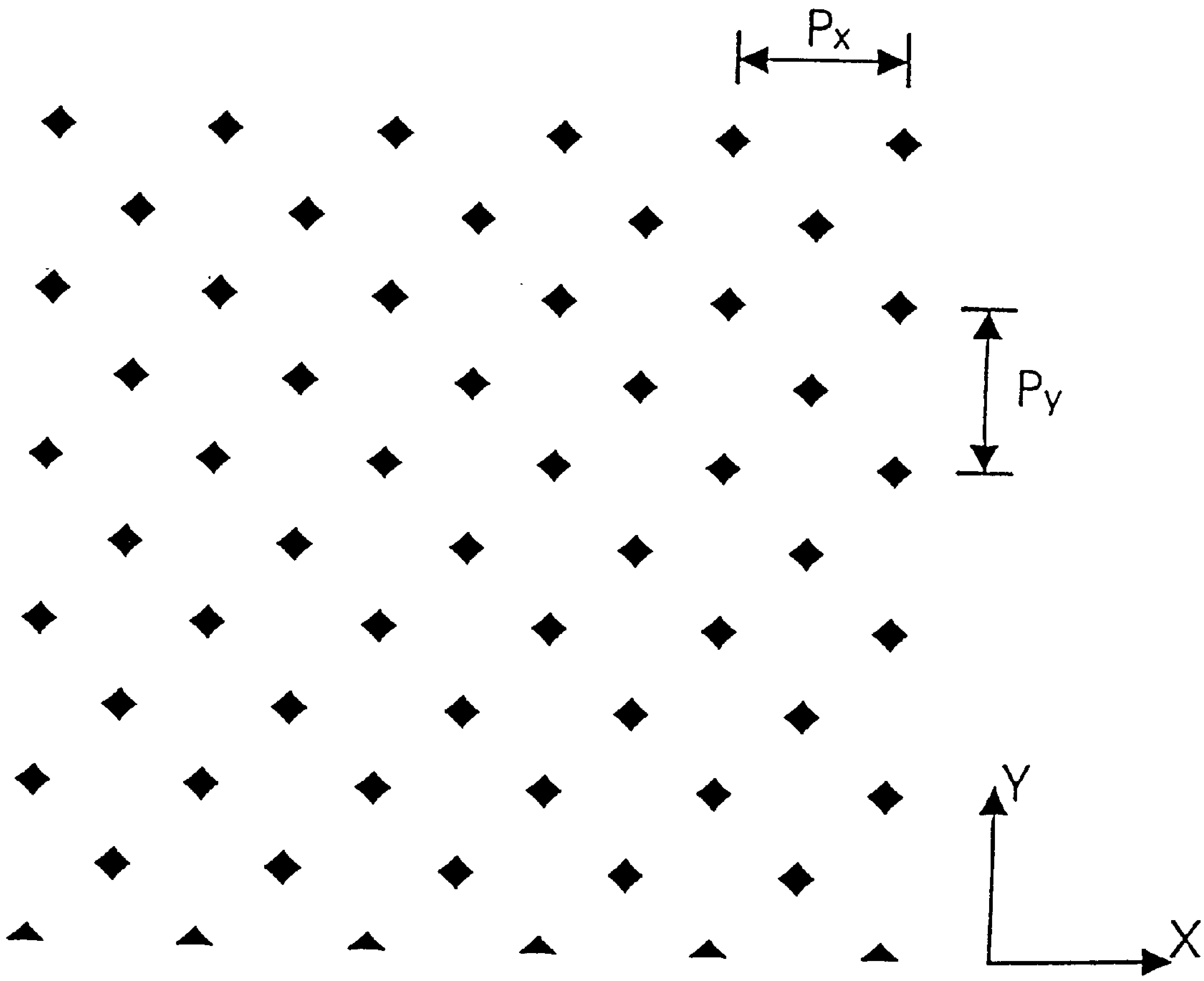

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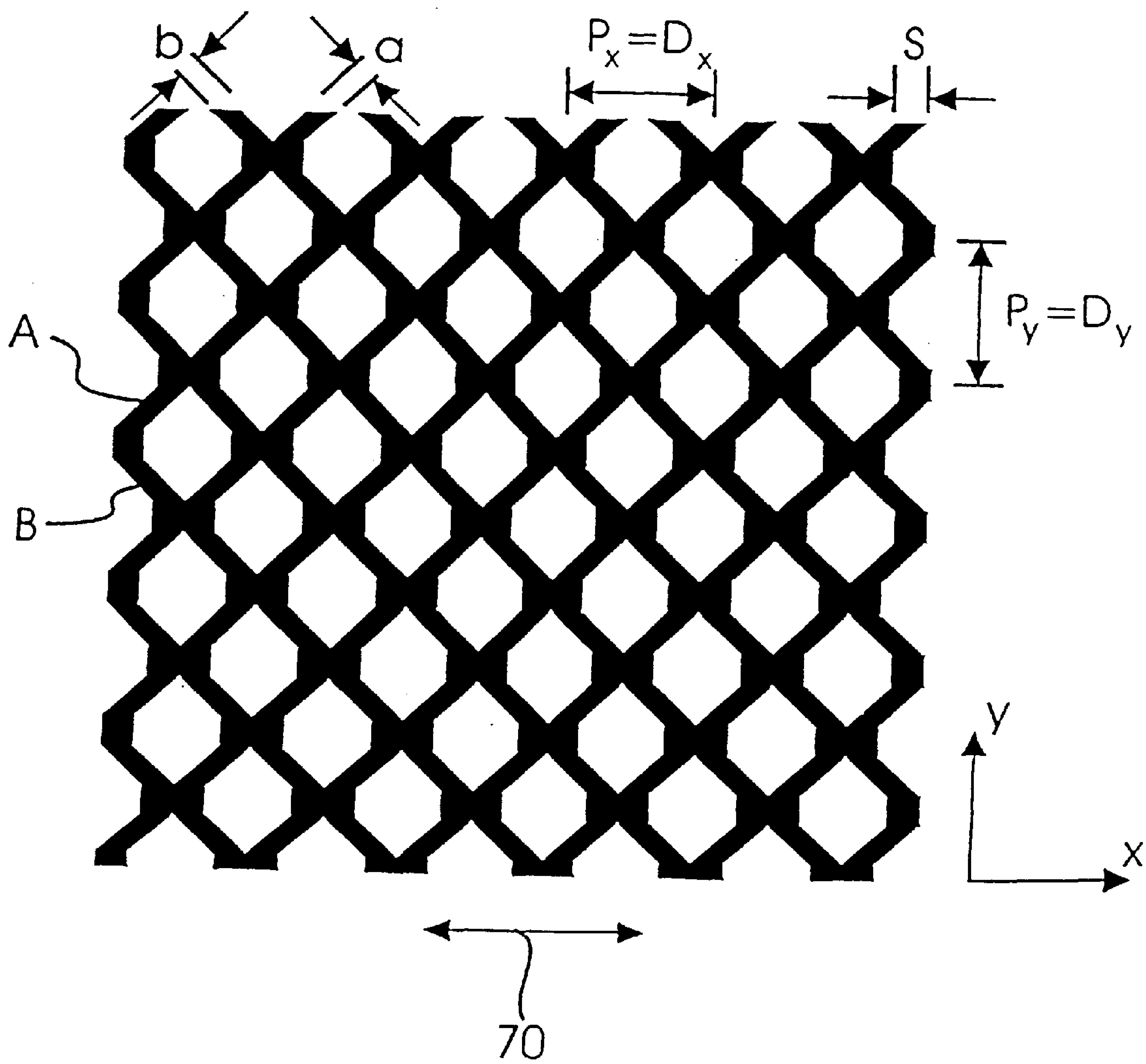

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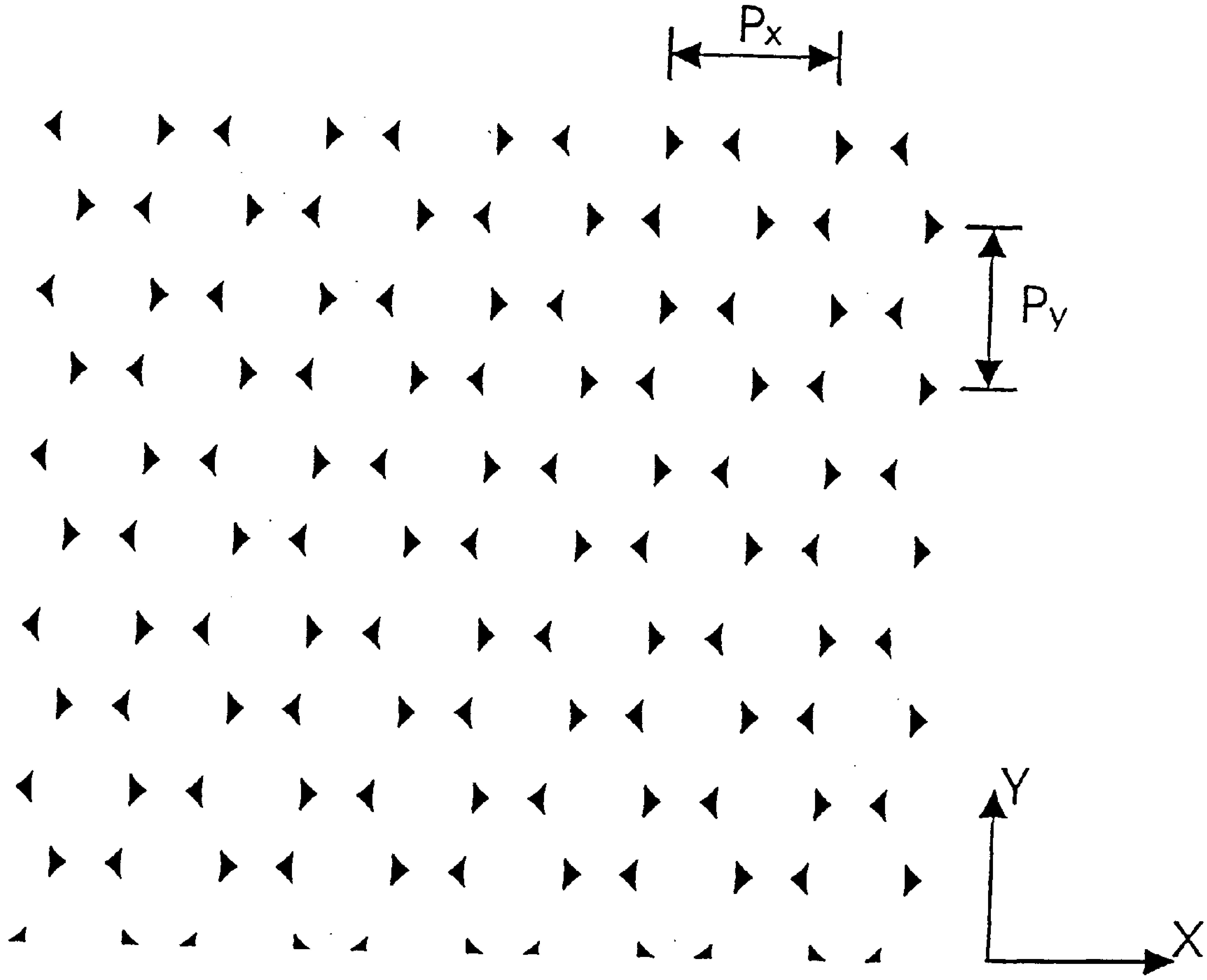

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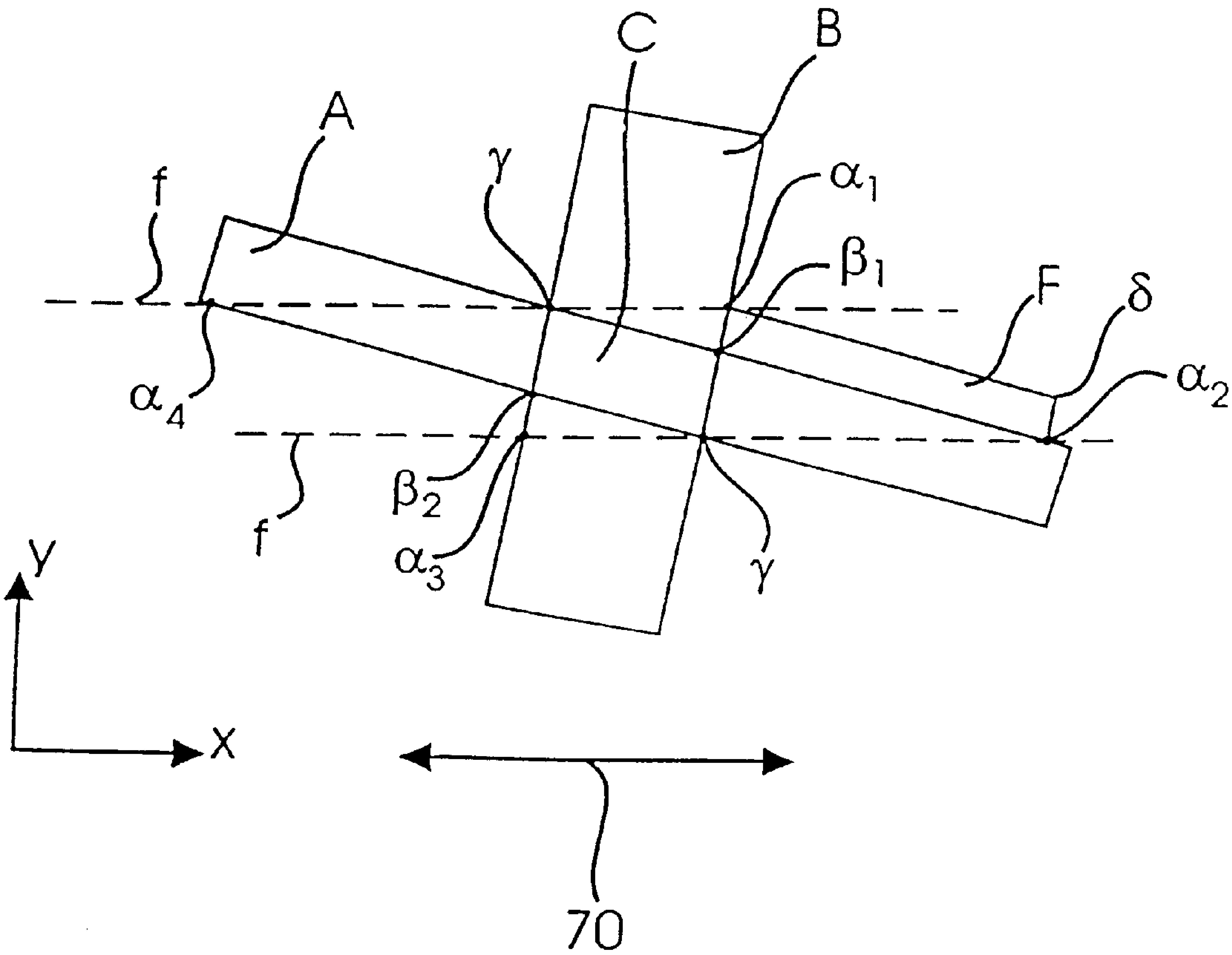
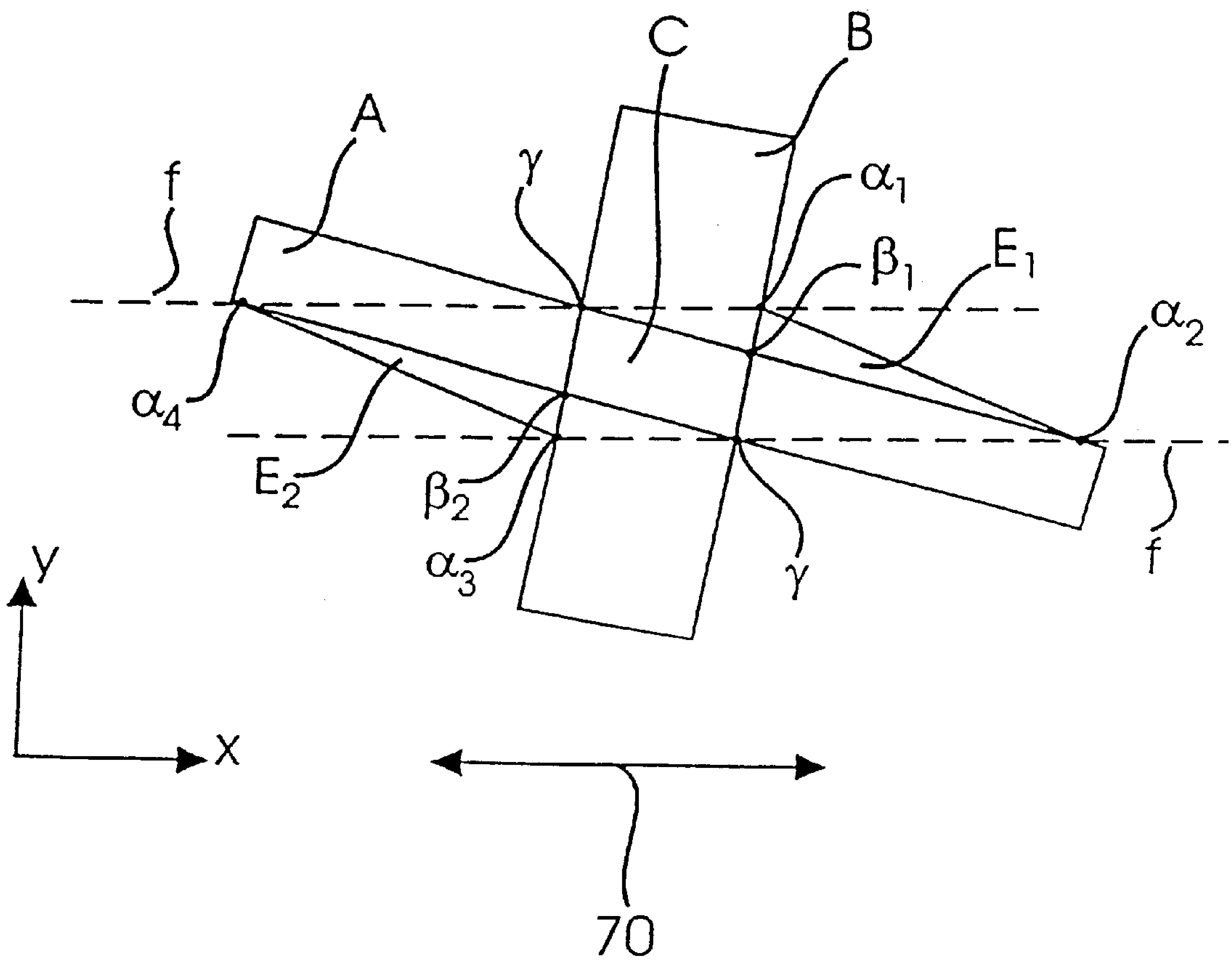


Fig. 12



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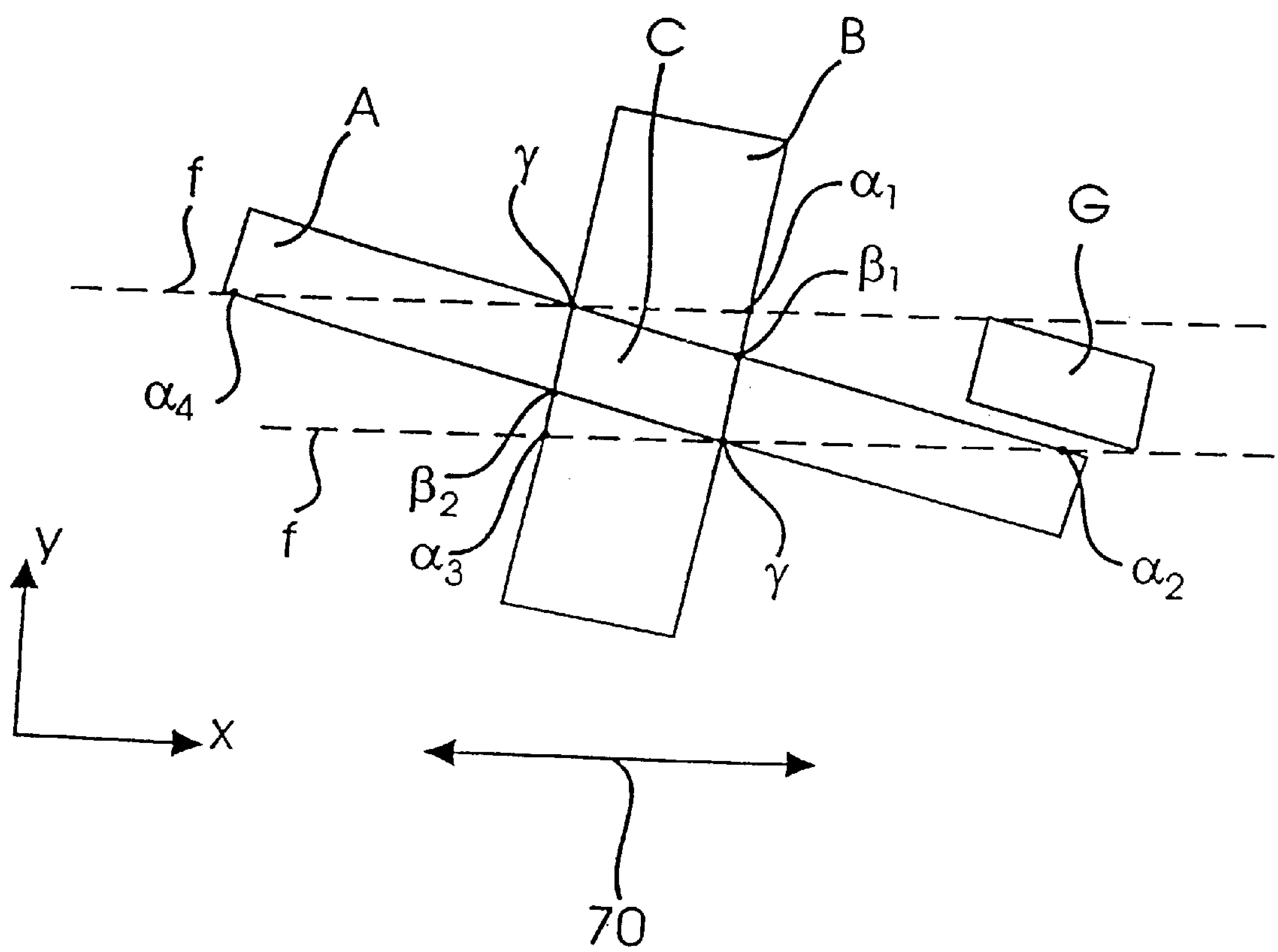

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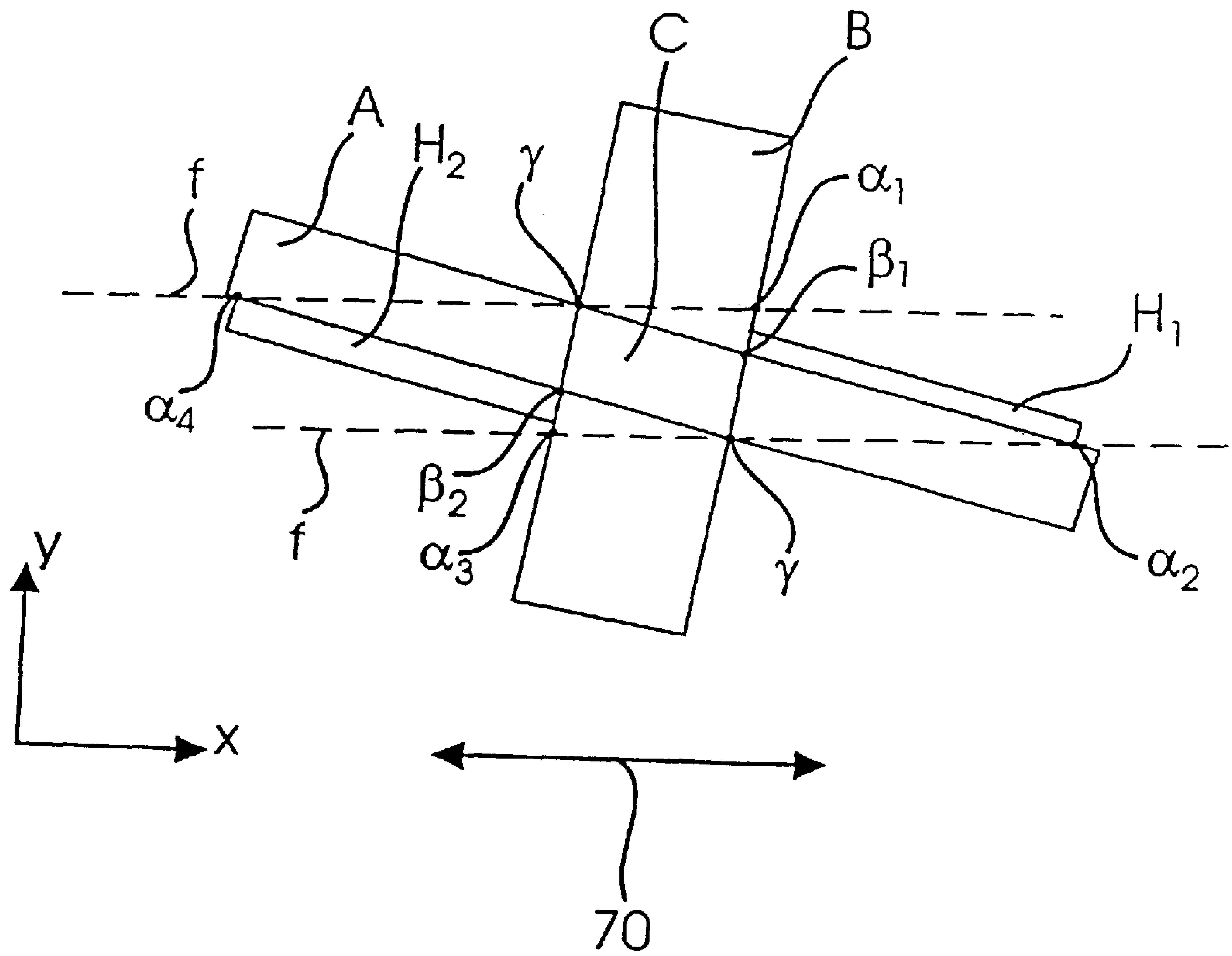

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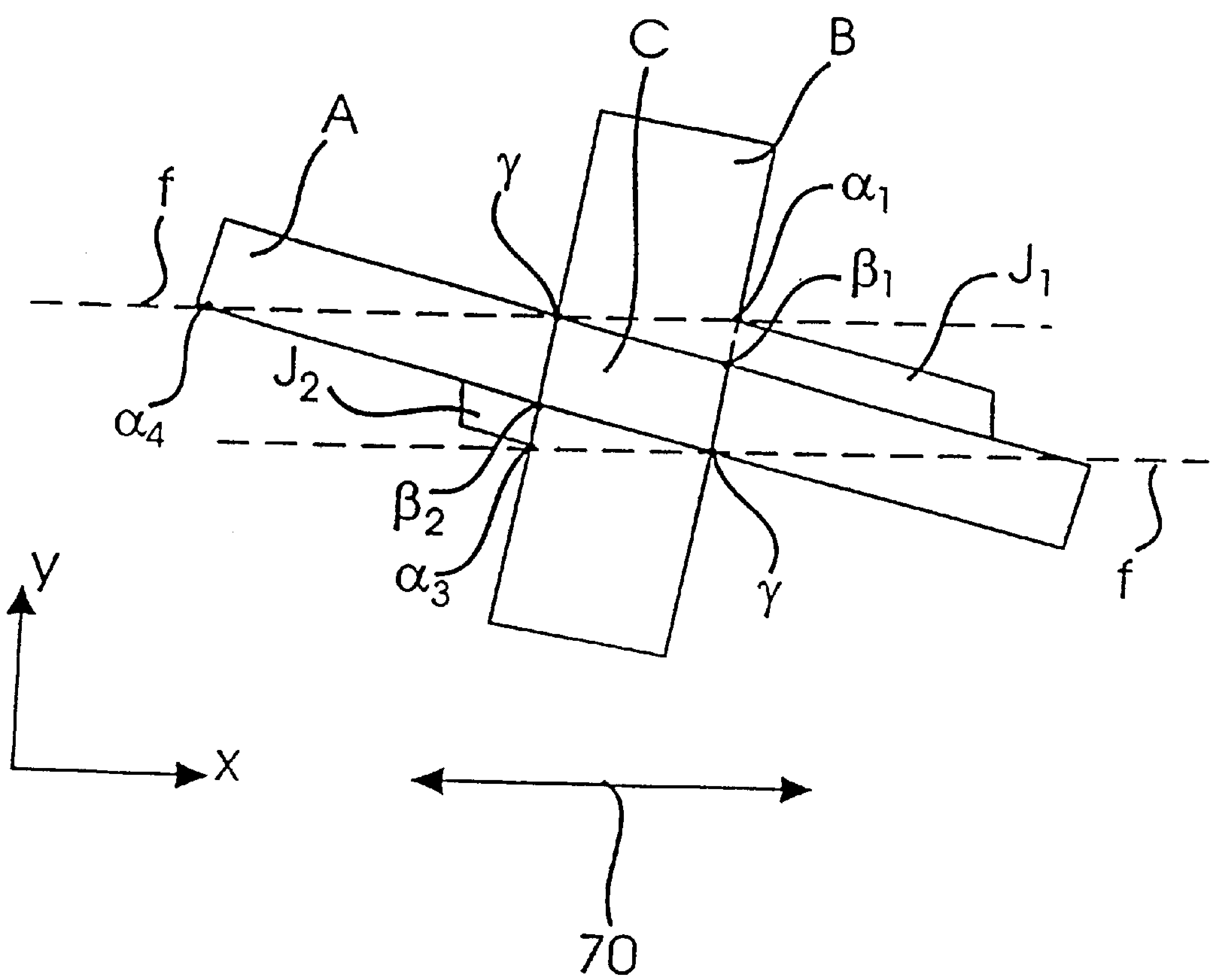

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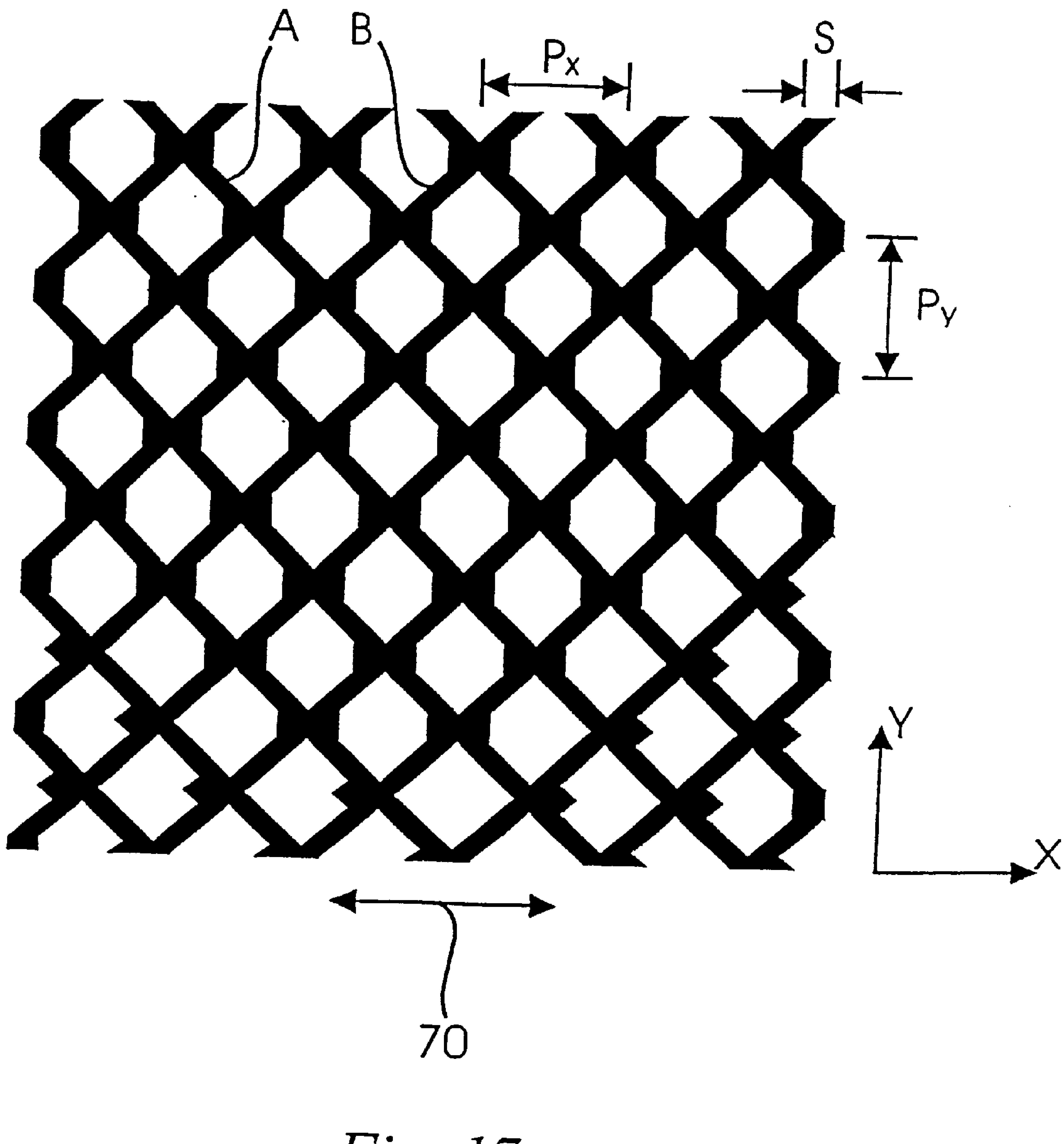

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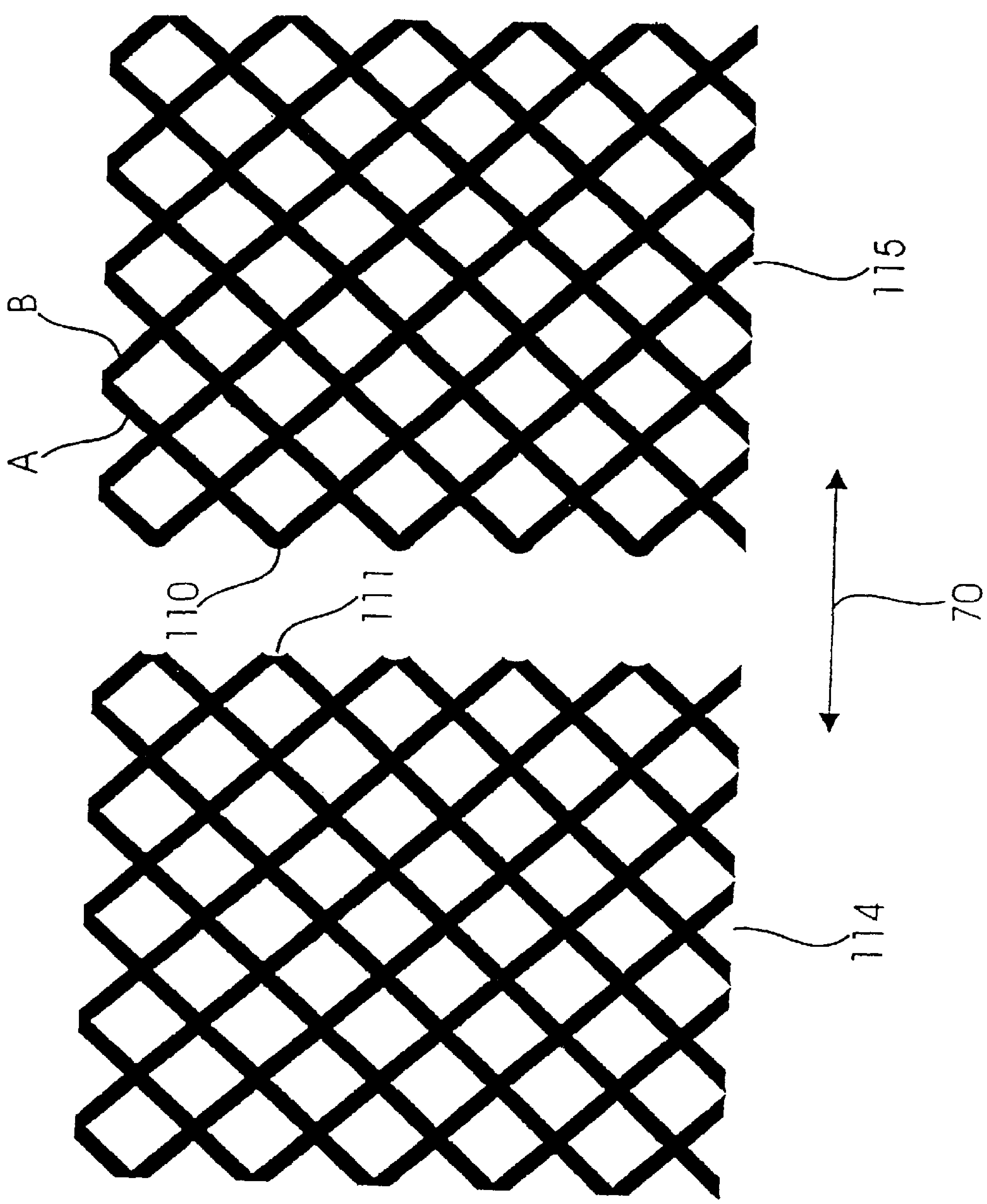

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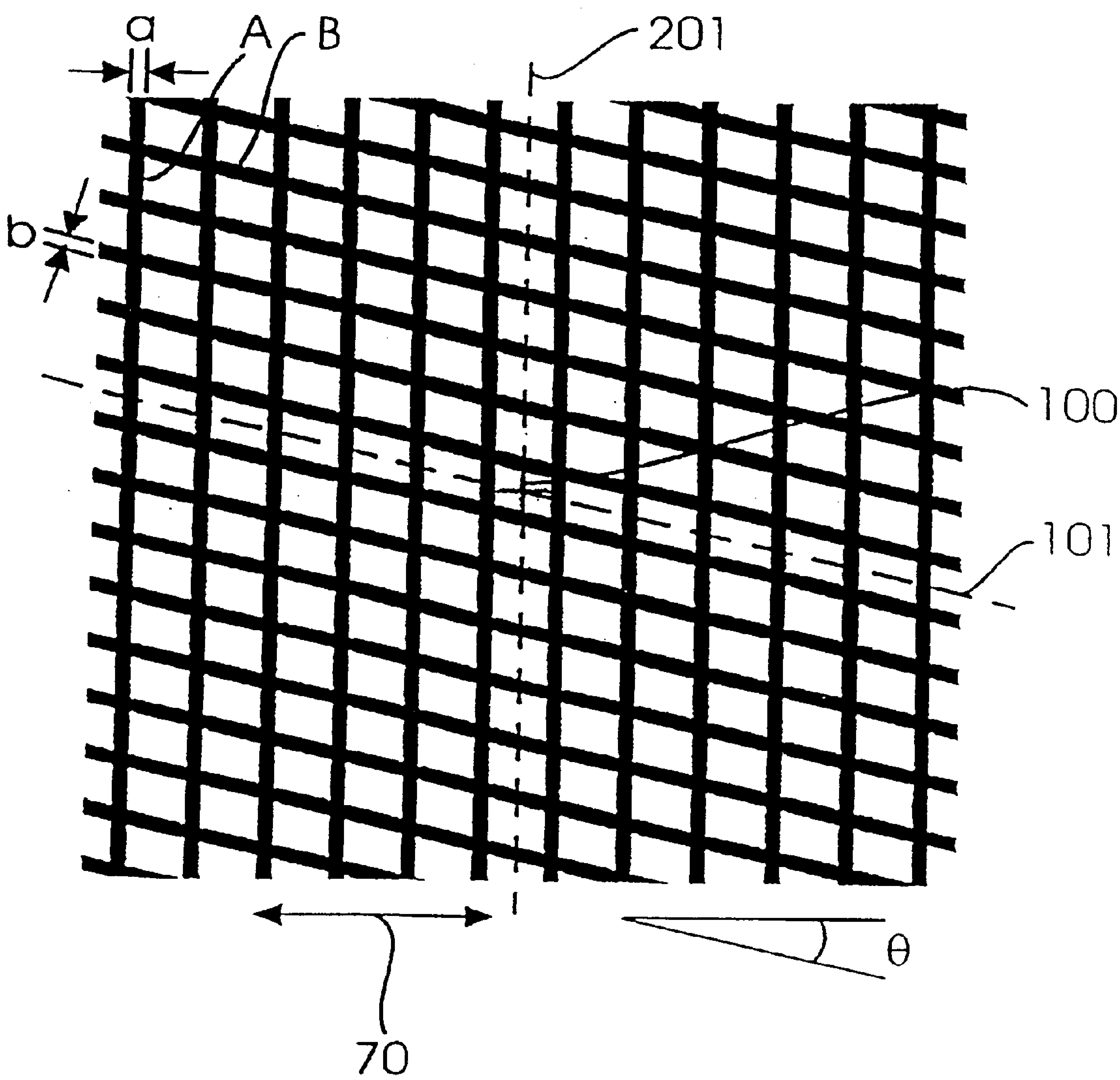

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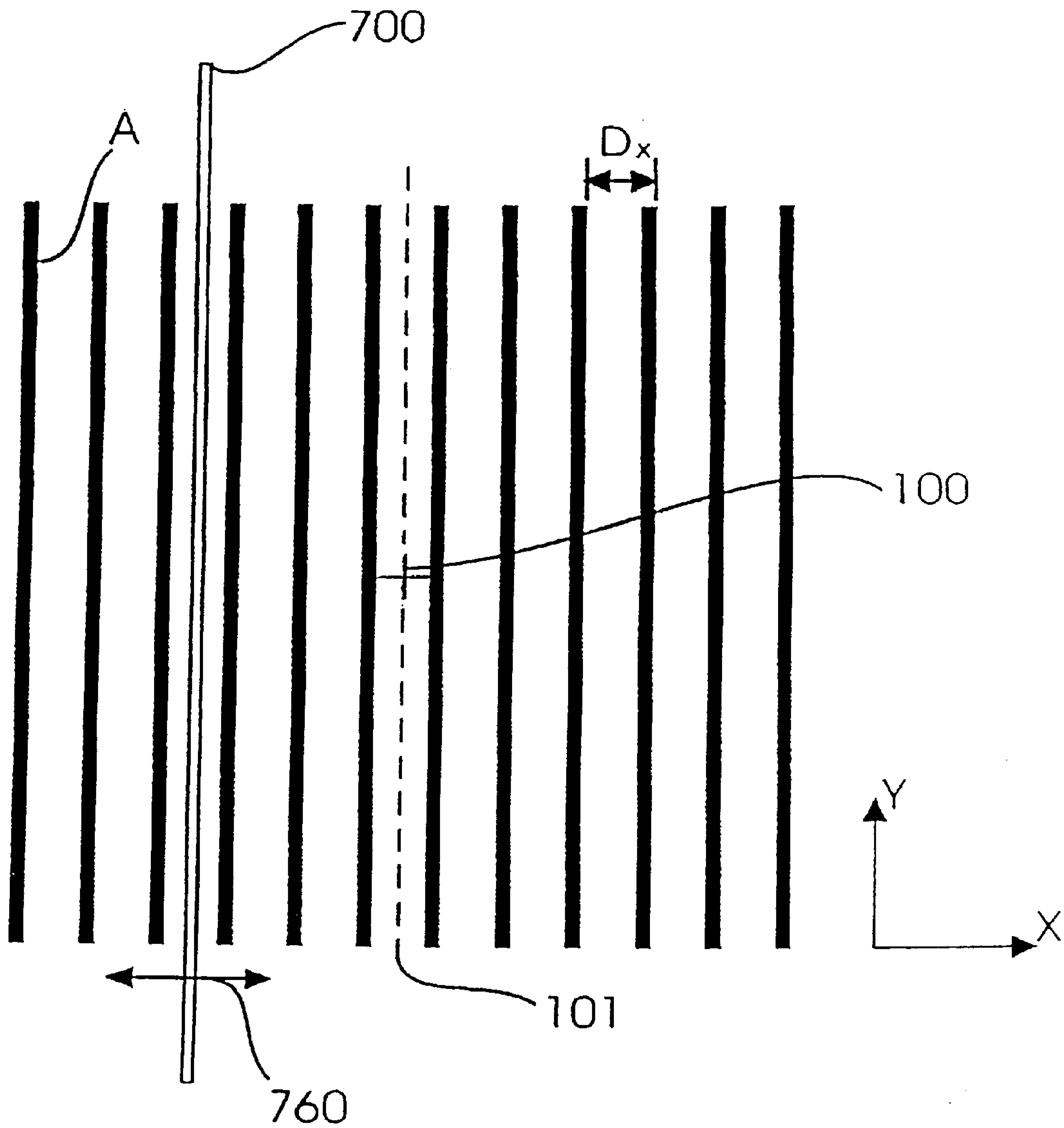
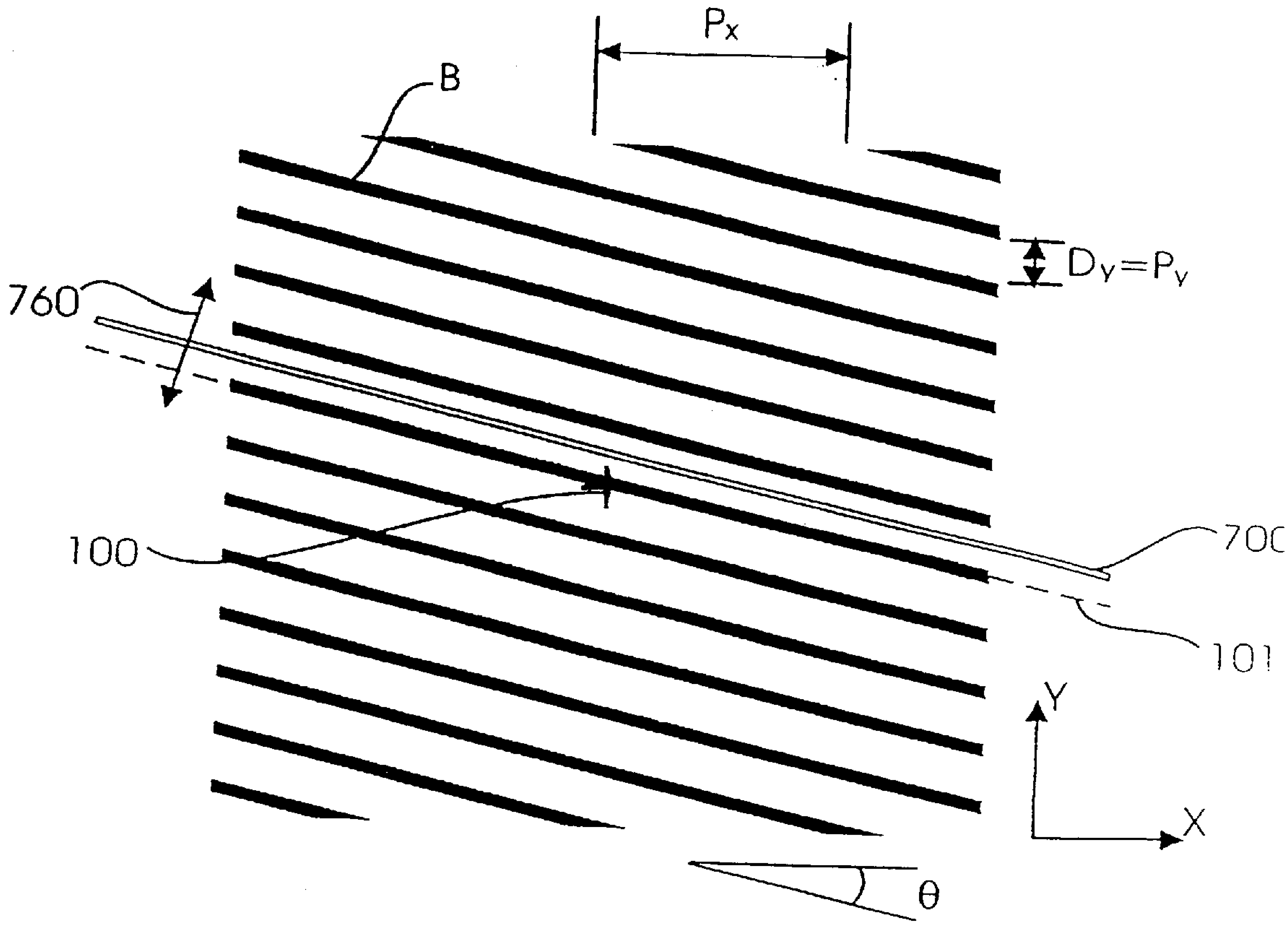


Fig. 20a



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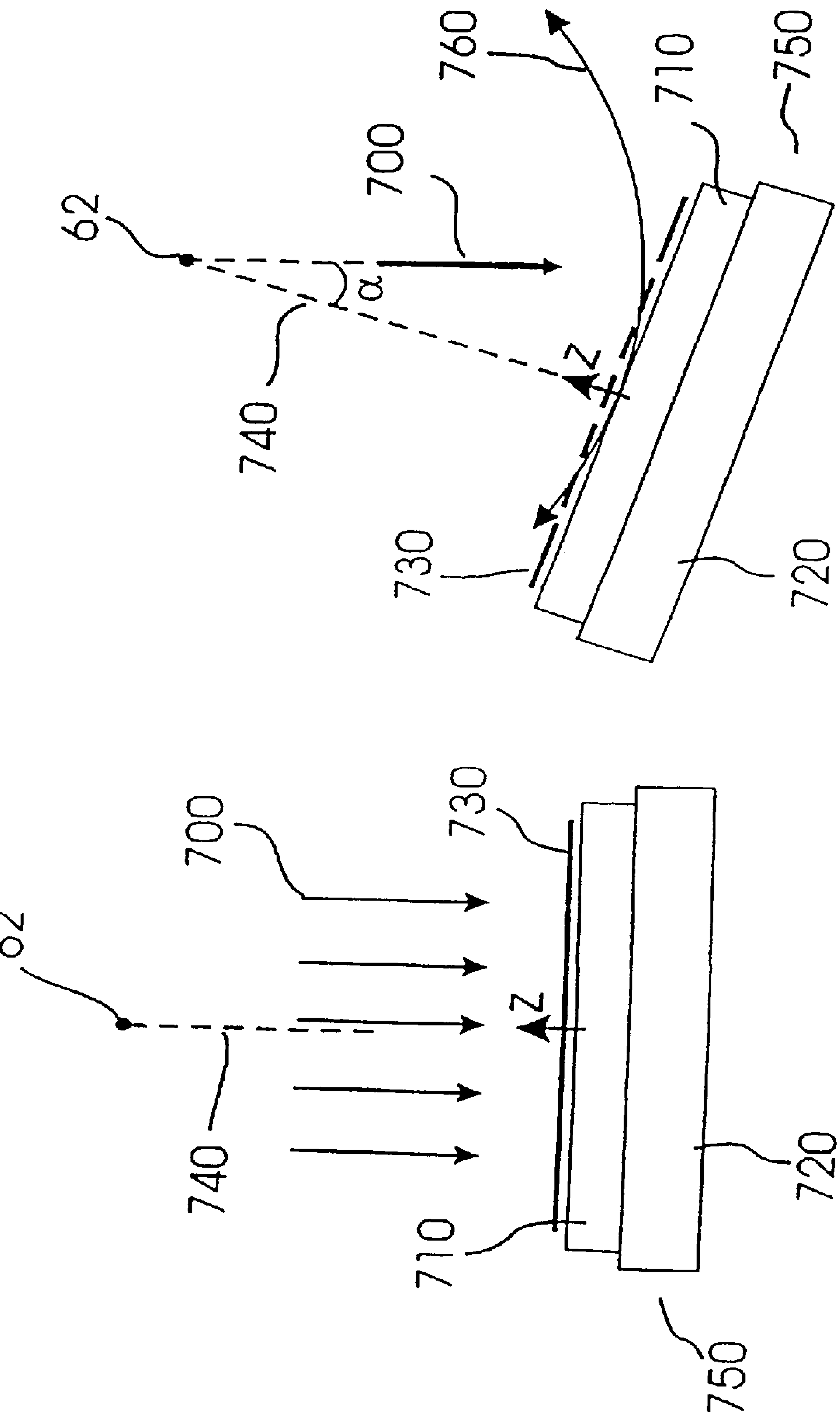


(a)

(b)

Fig. 21

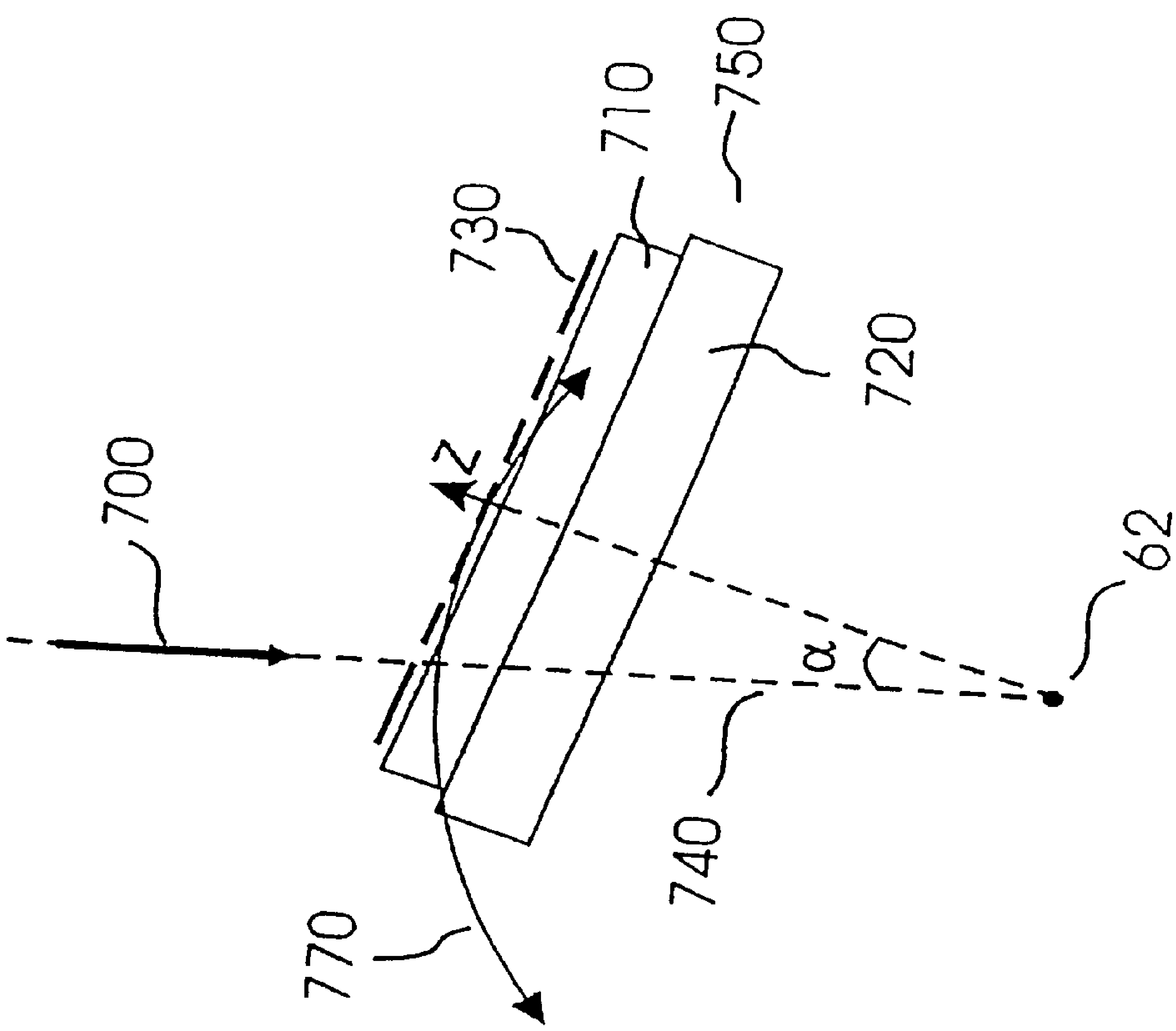


Fig. 21c

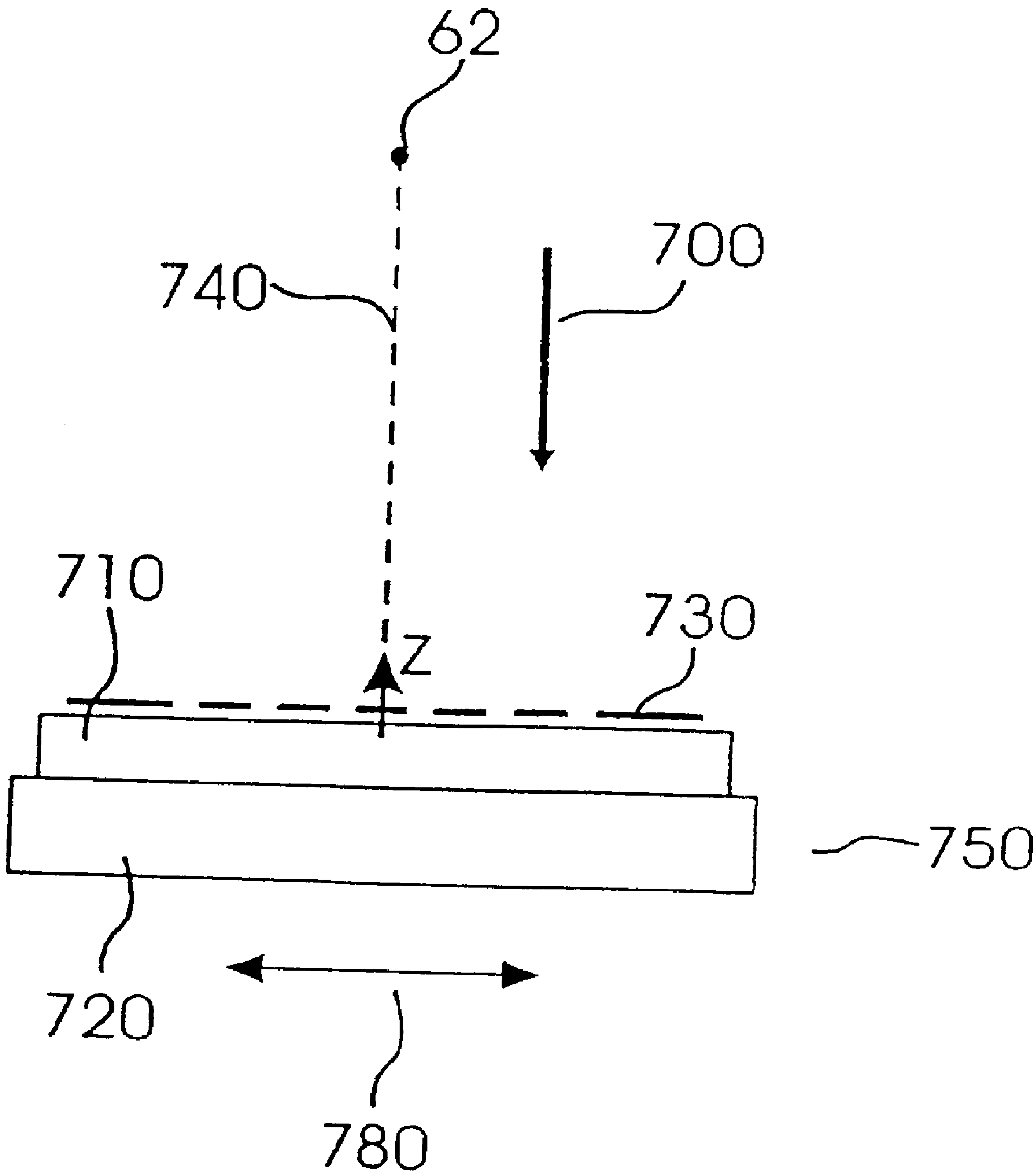


Fig. 22

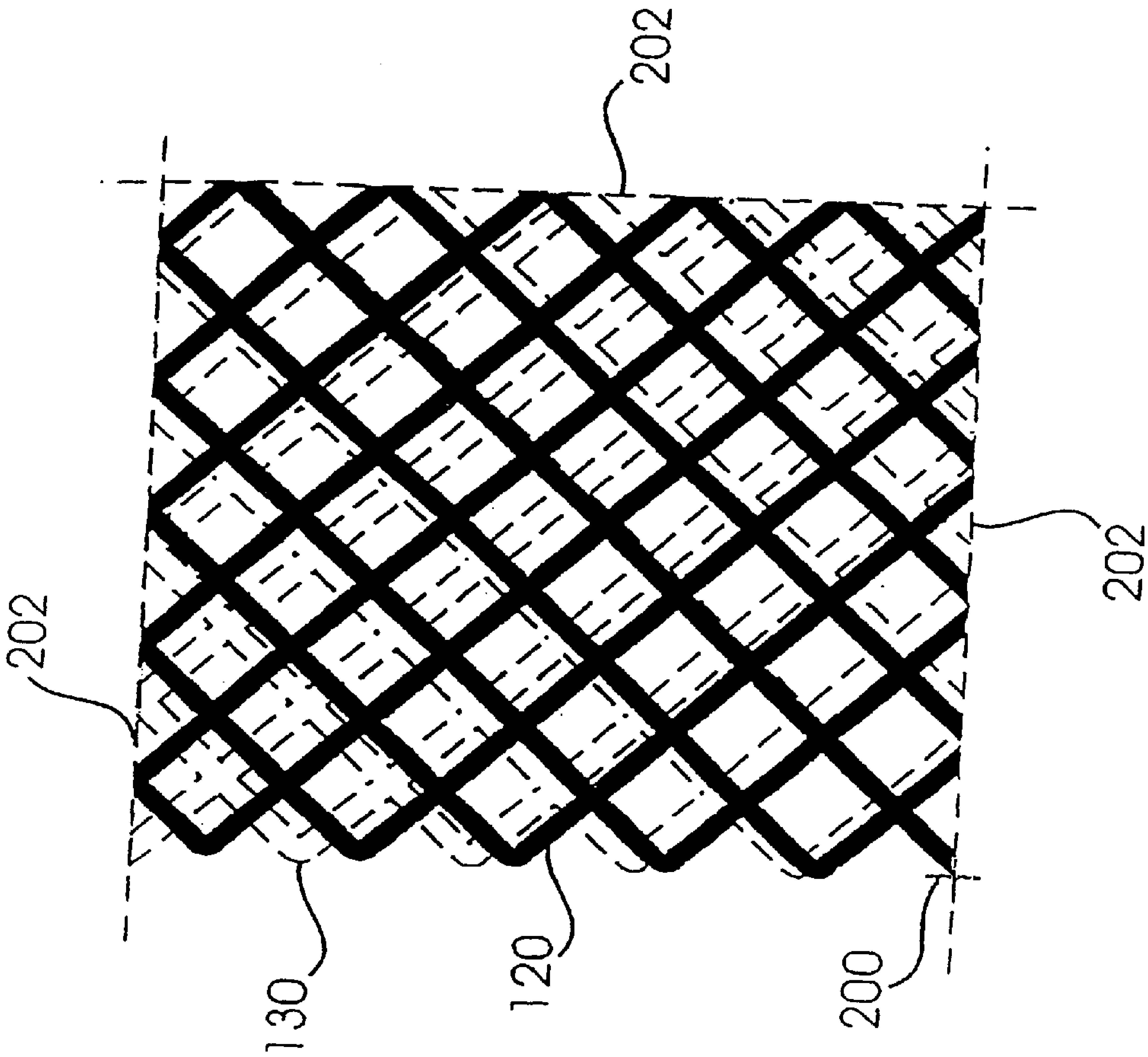


Fig. 23

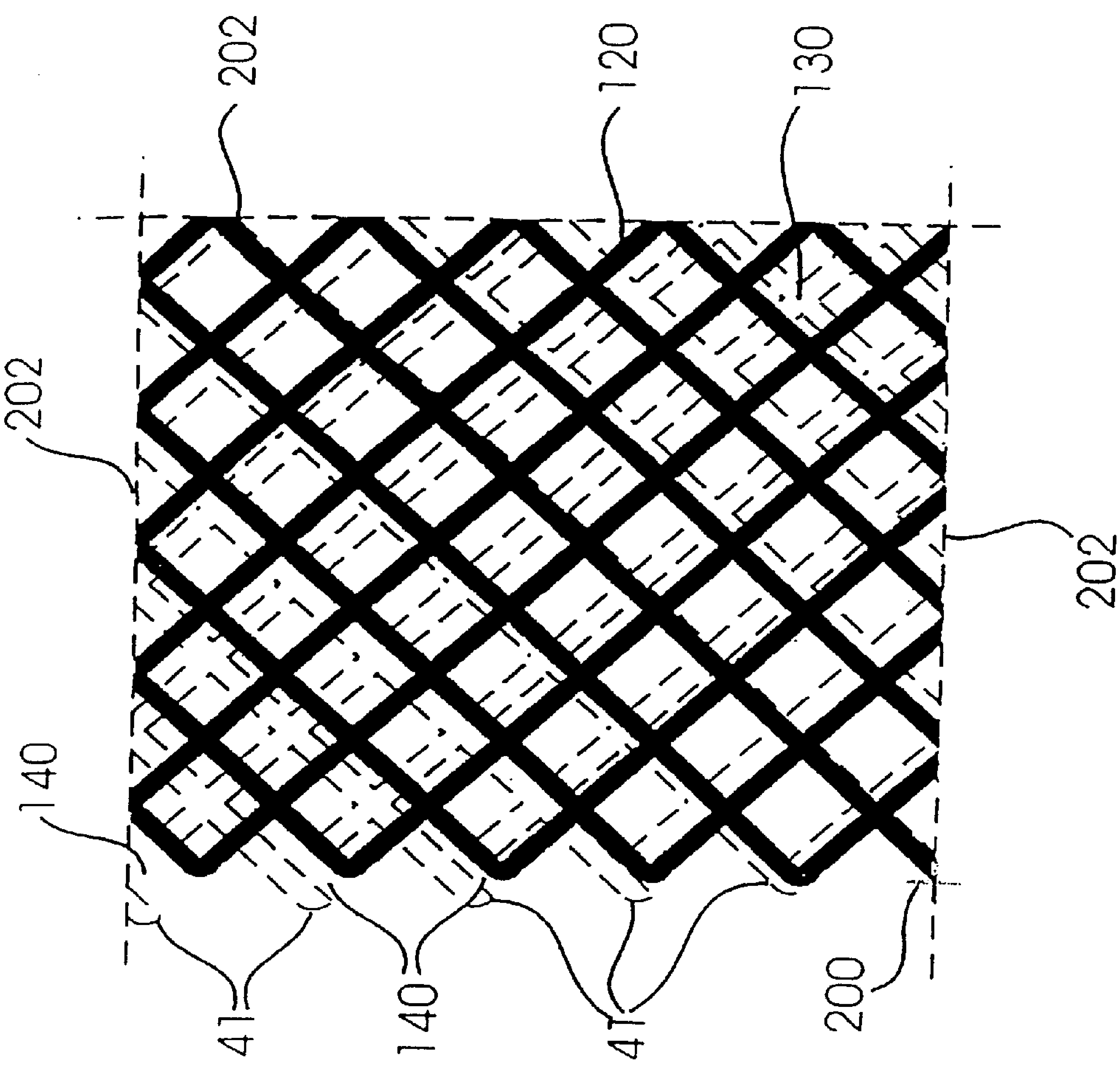


Fig. 24

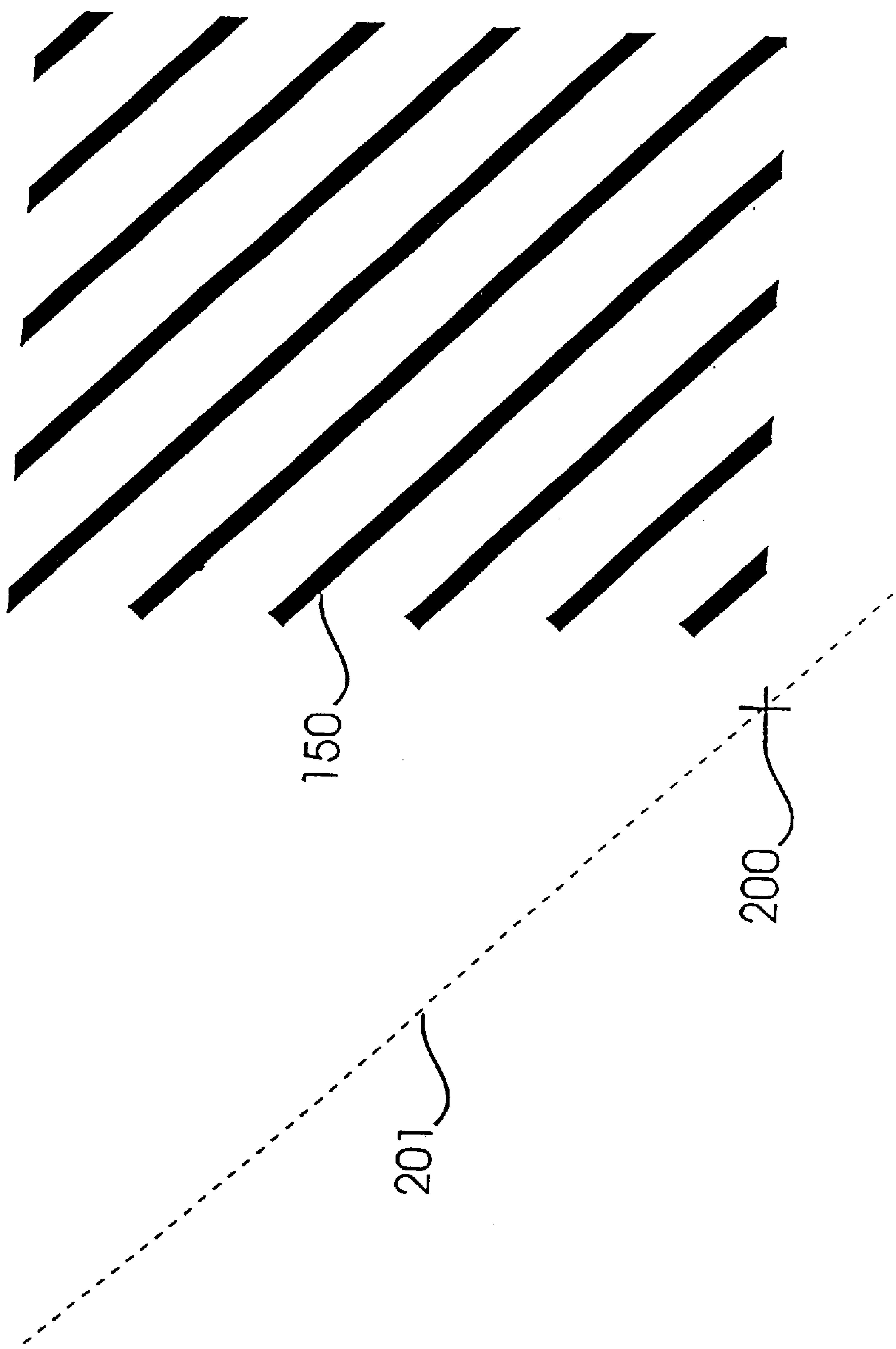
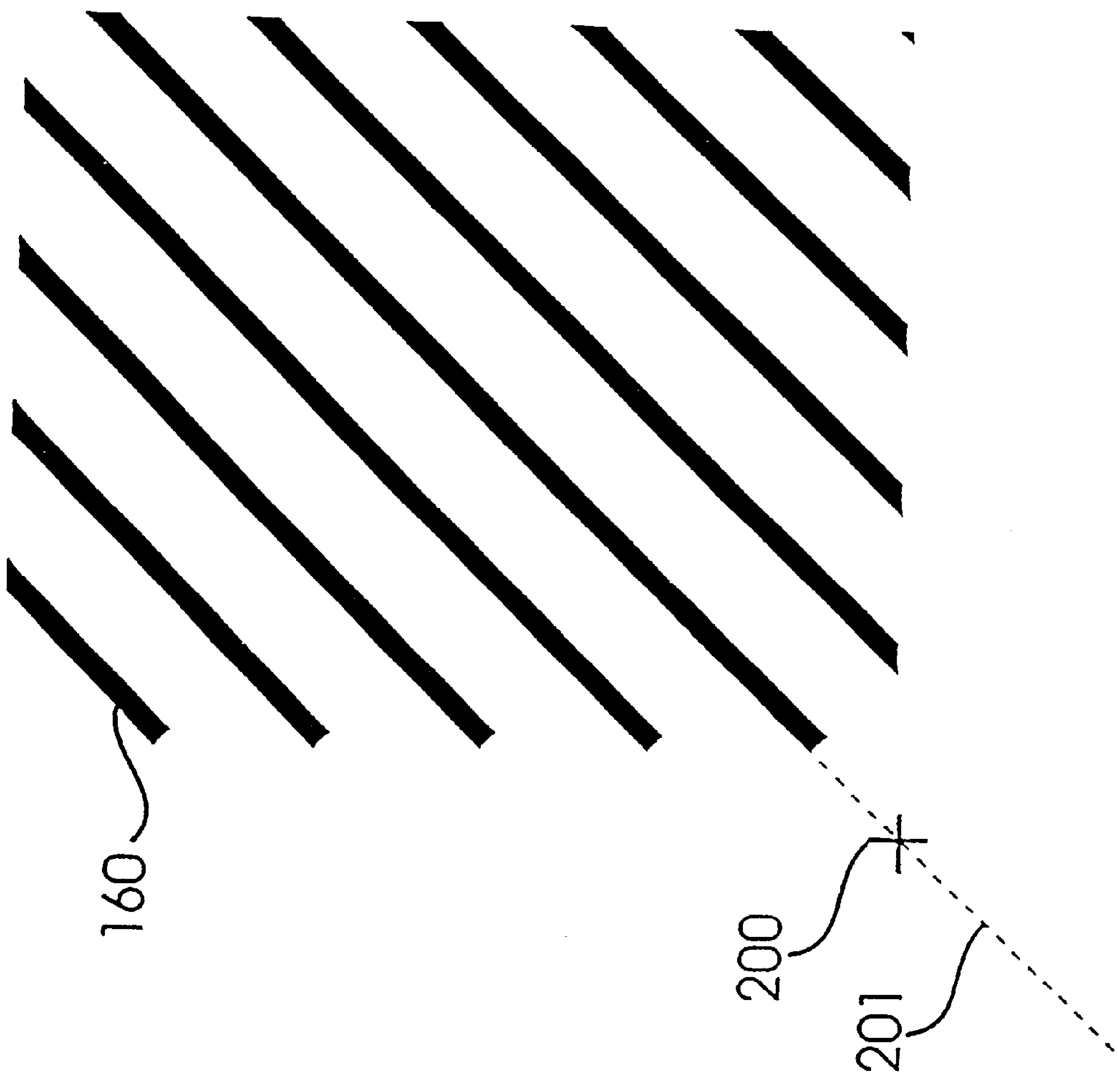


Fig. 25a



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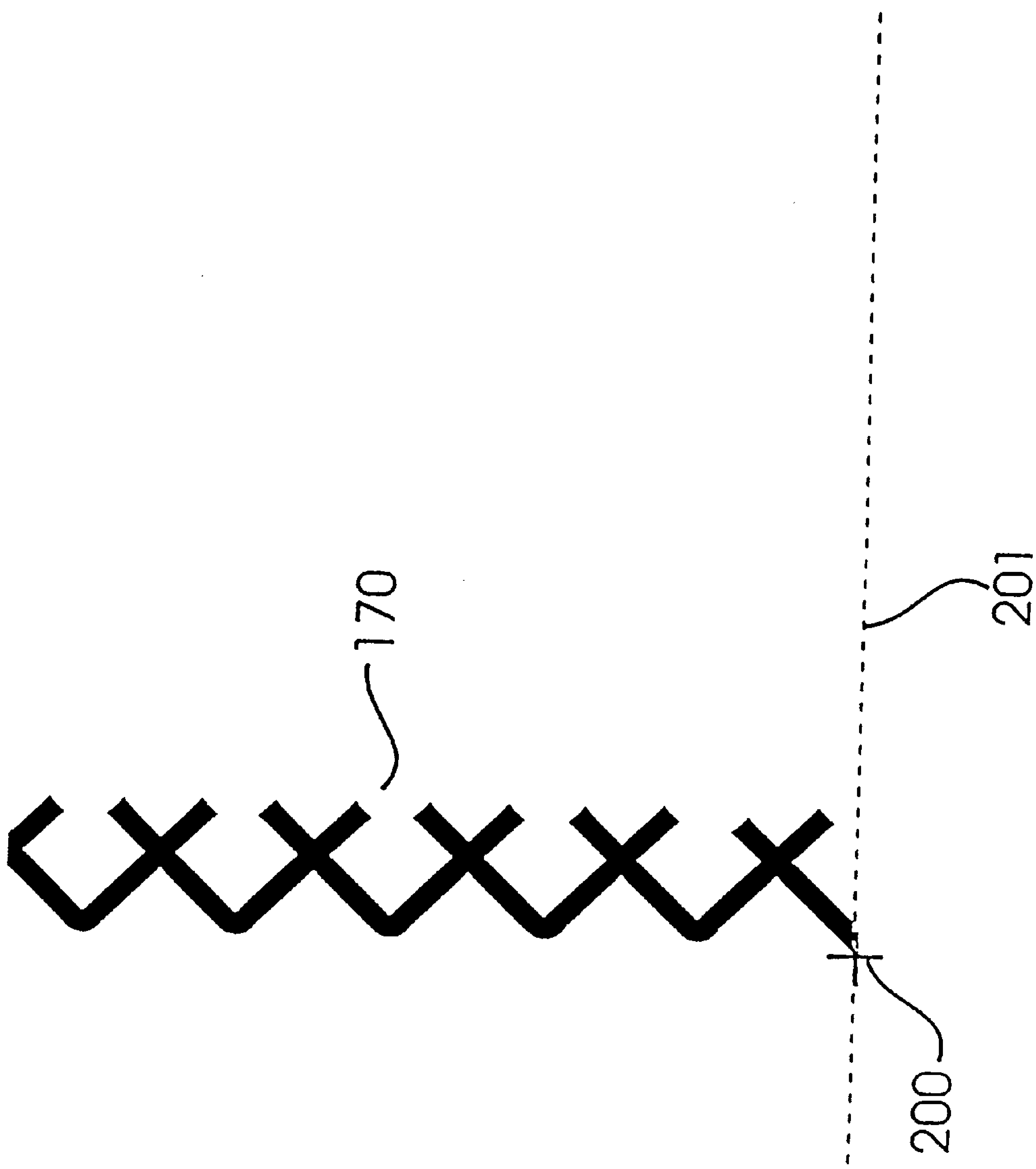
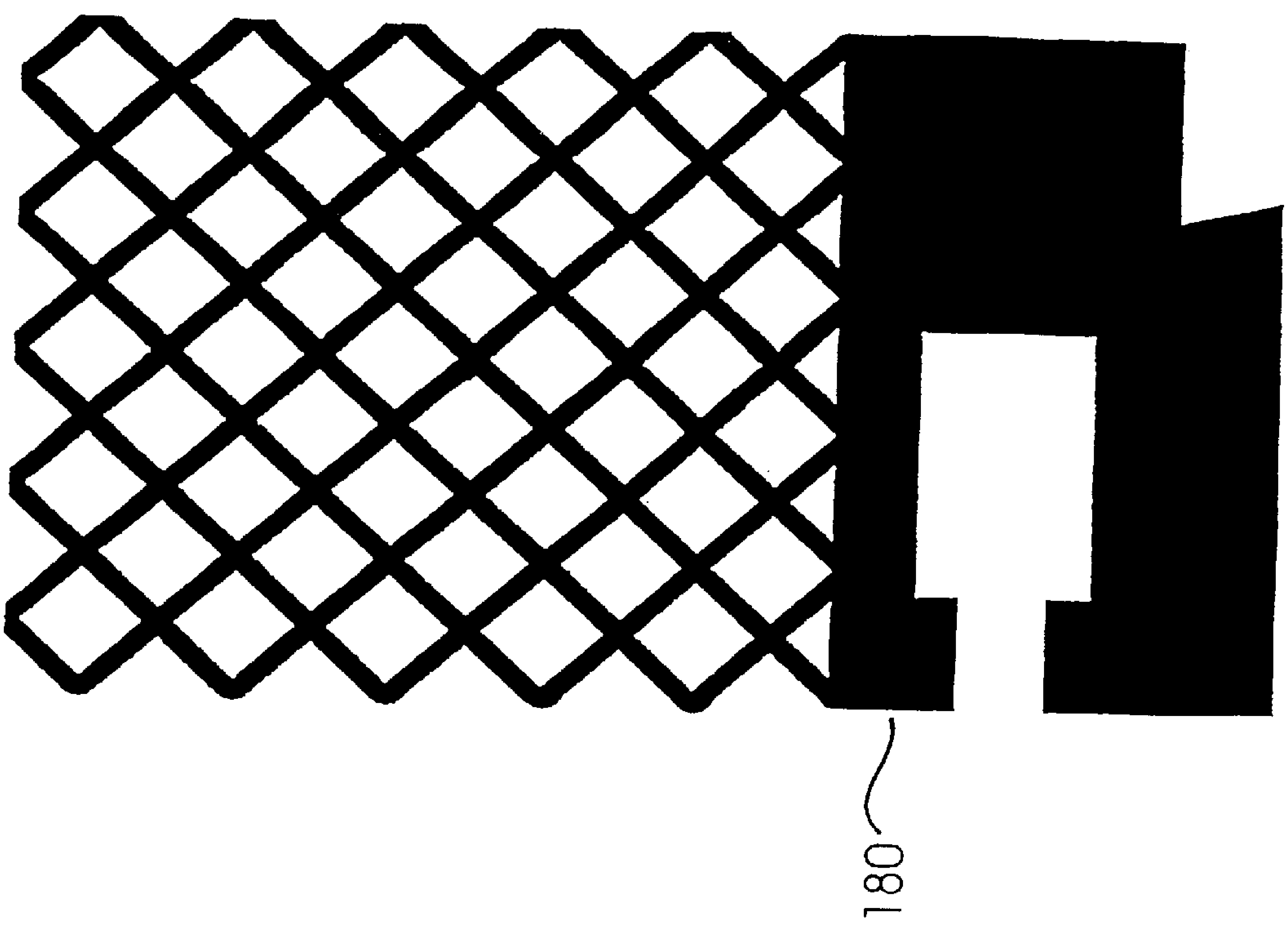


Fig. 25c



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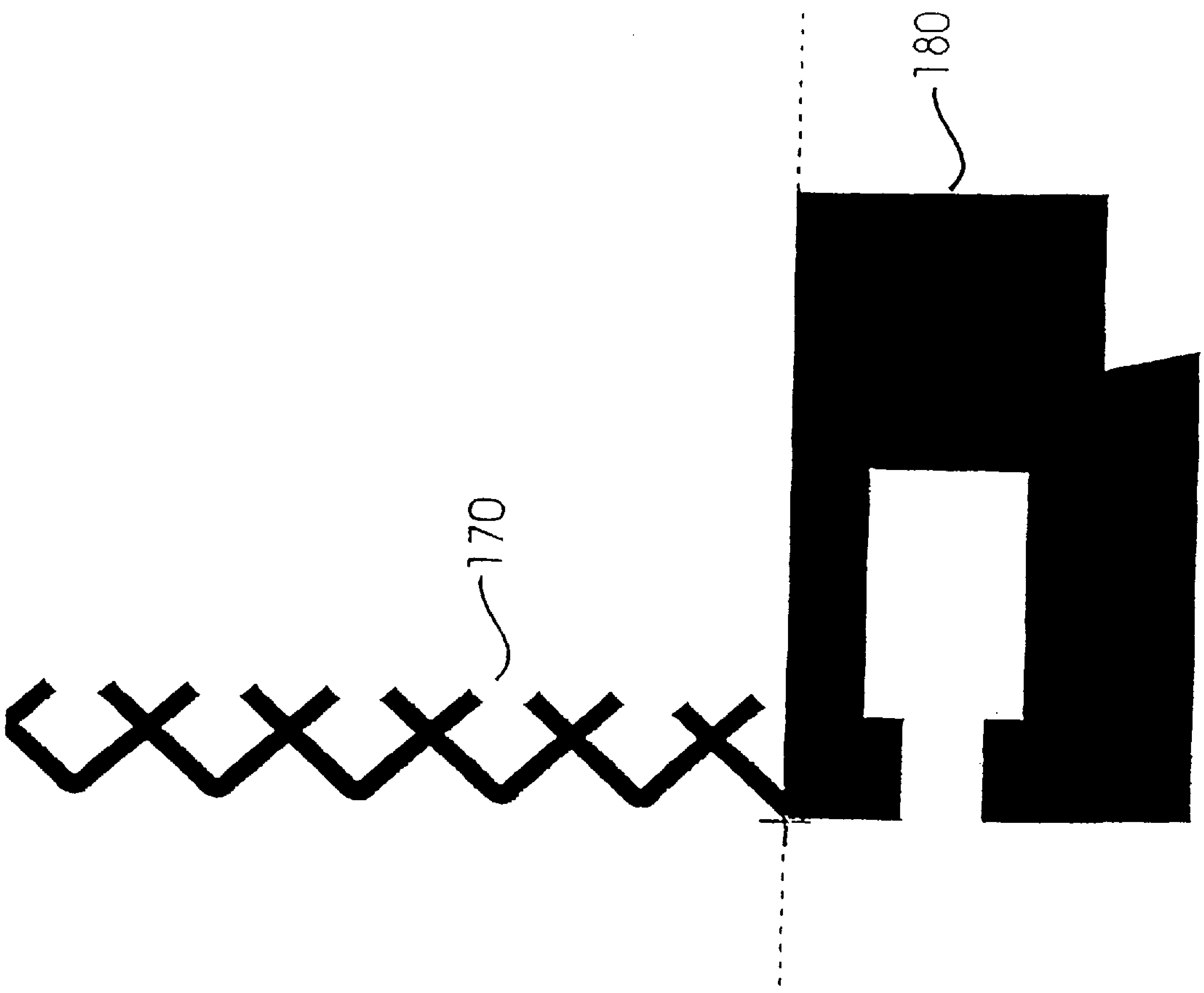

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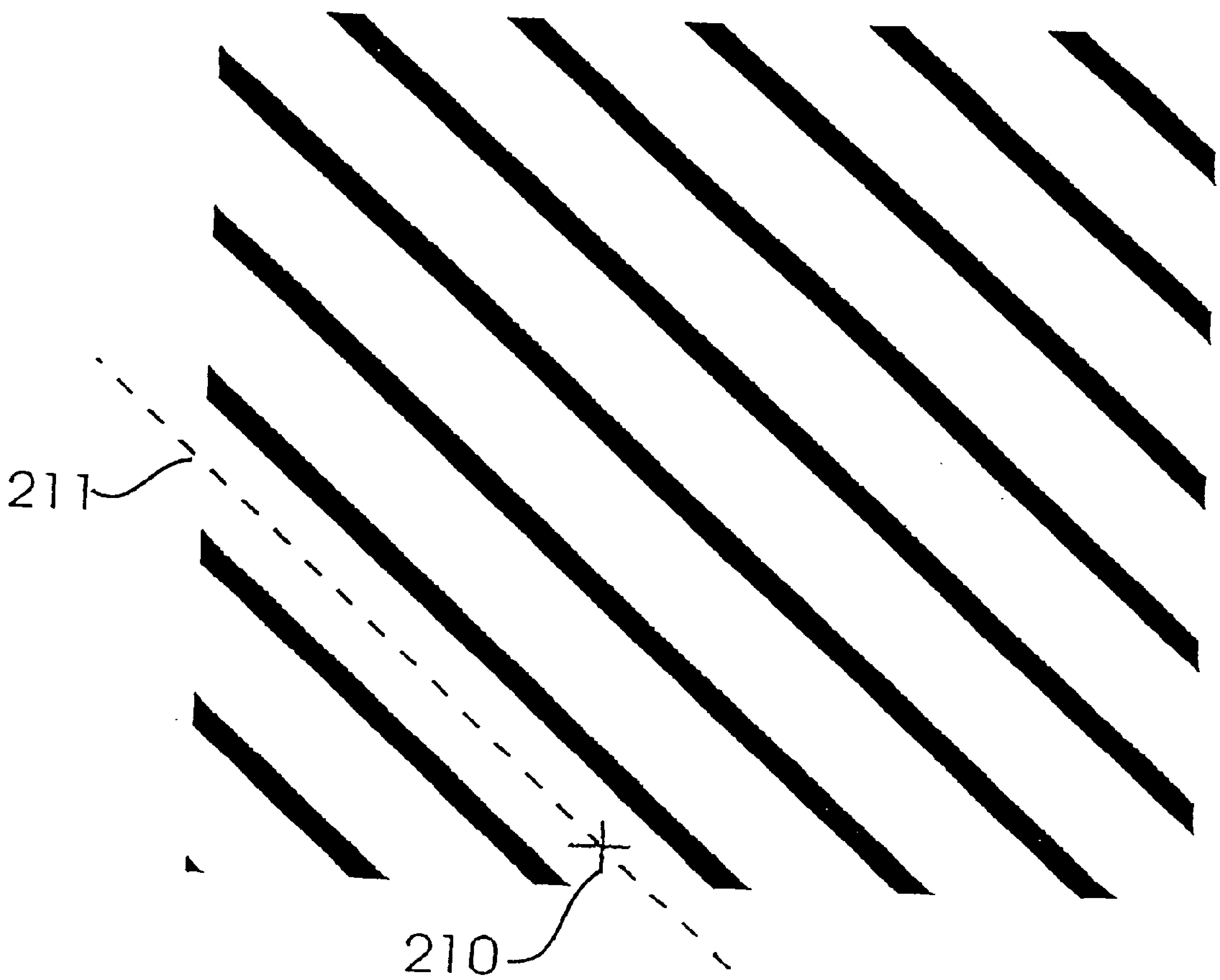


Fig. 28a

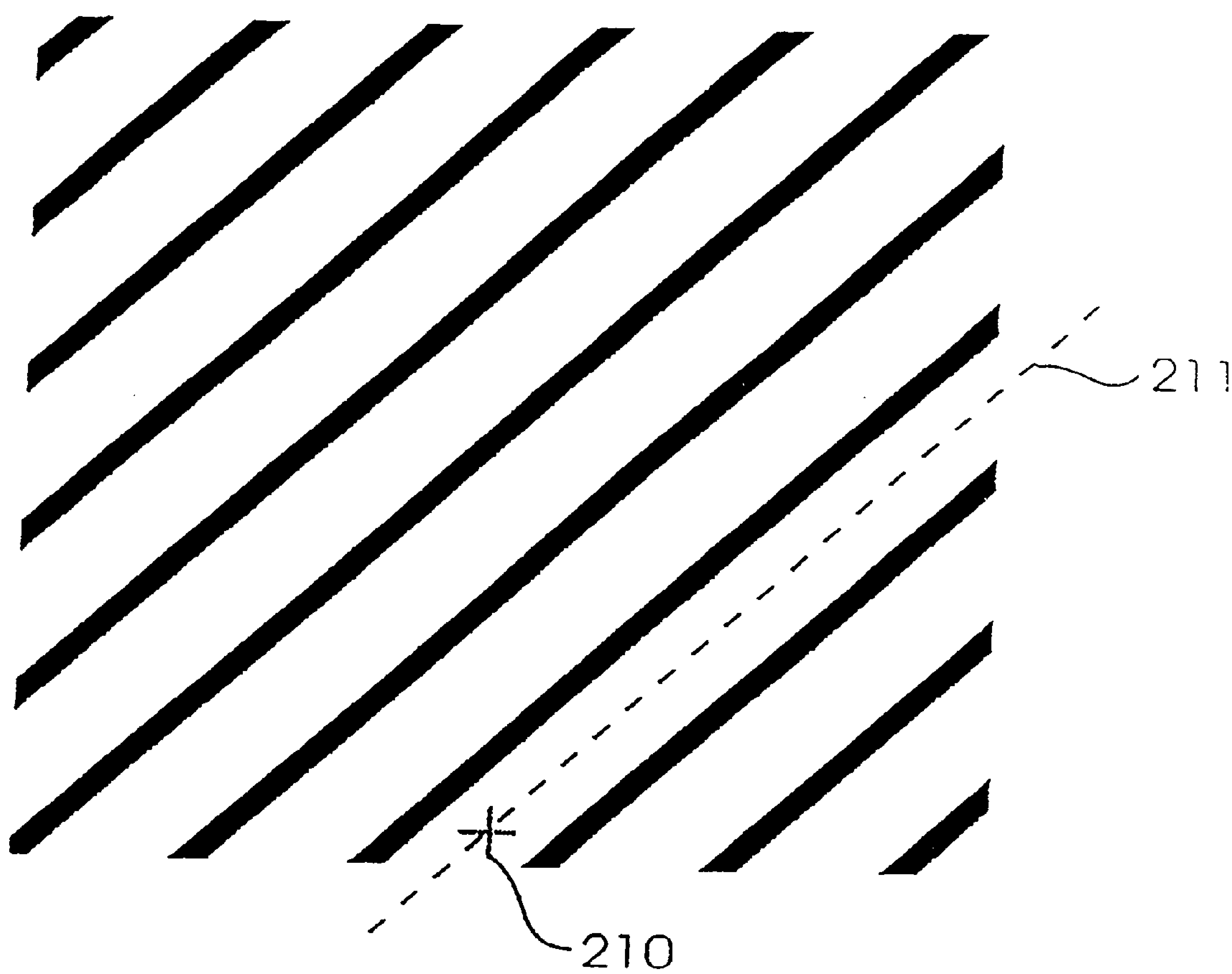
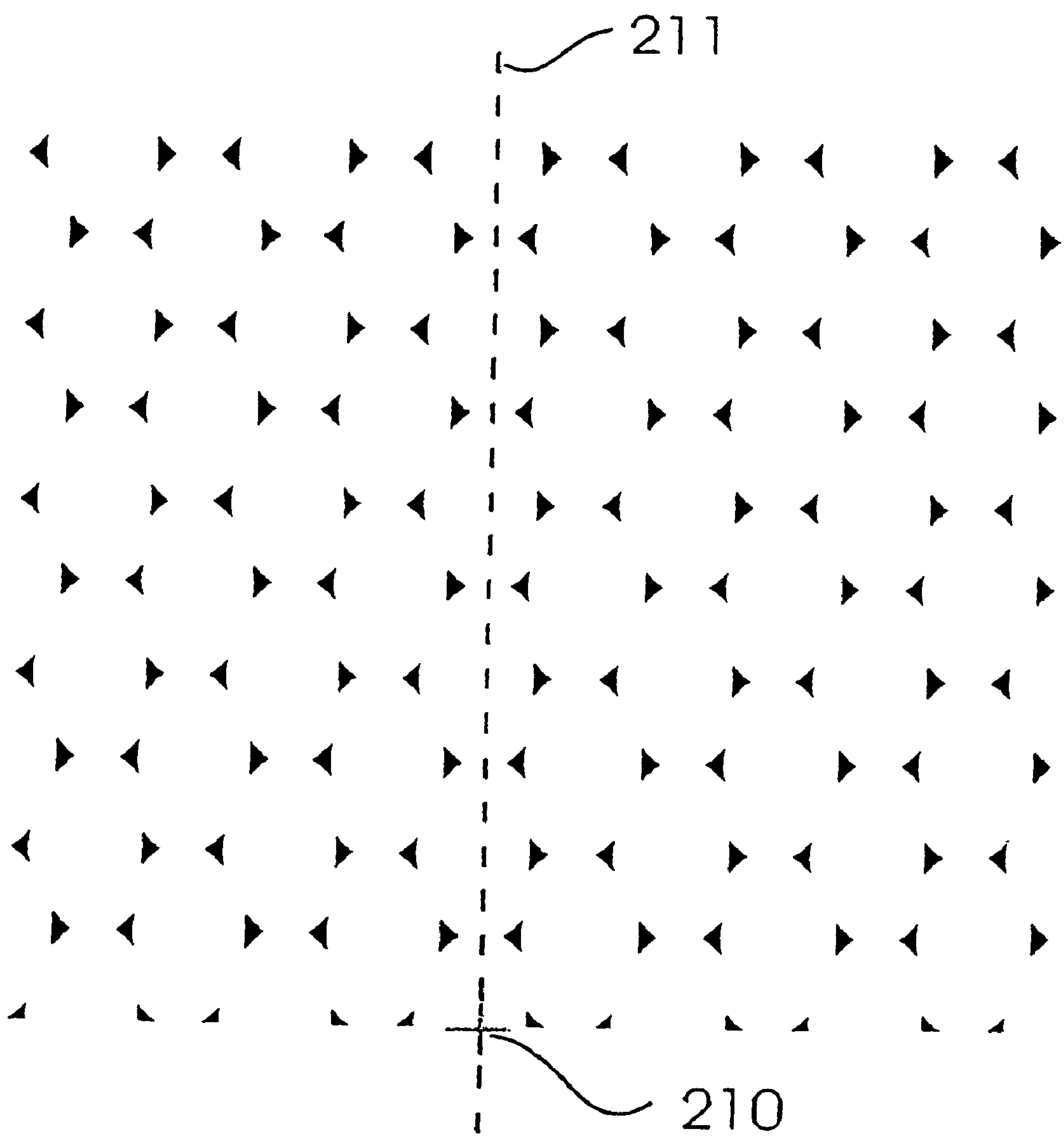


Fig. 28b



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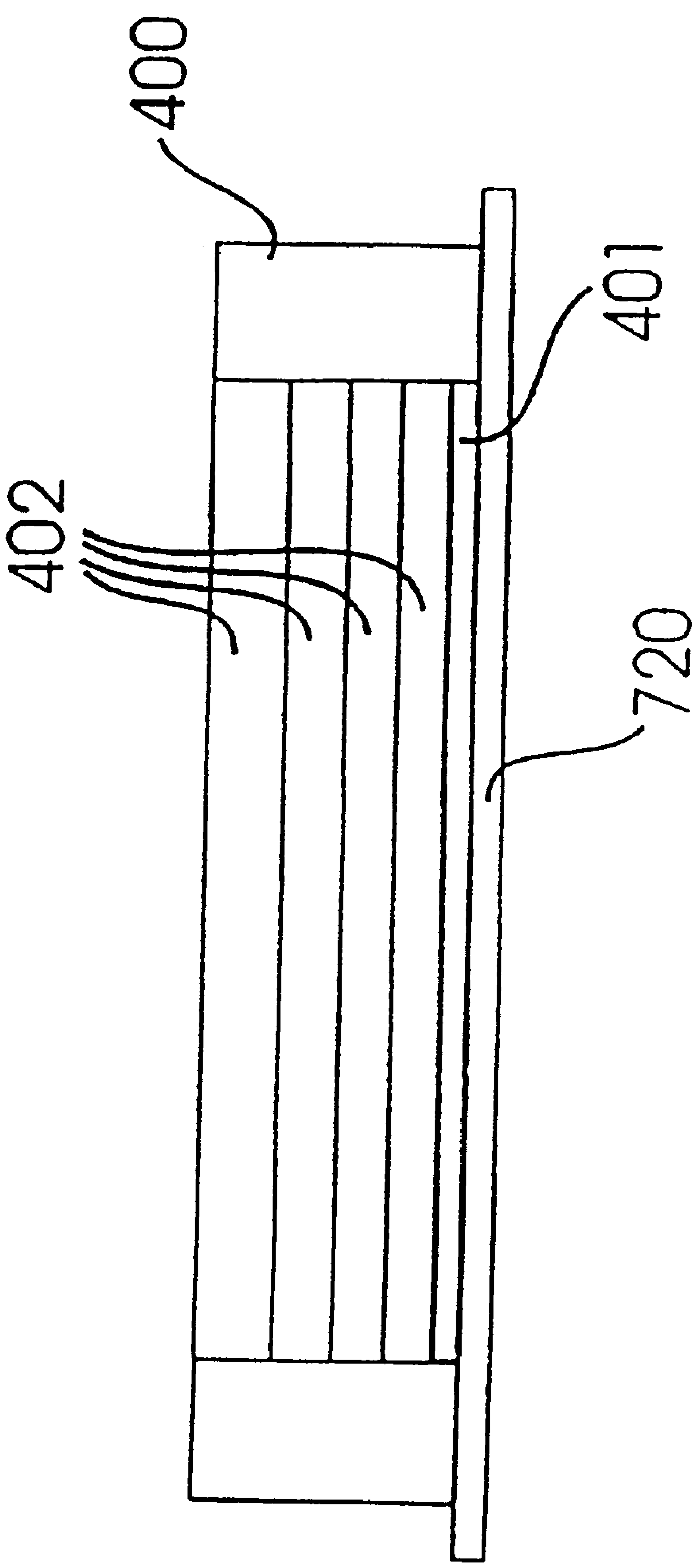

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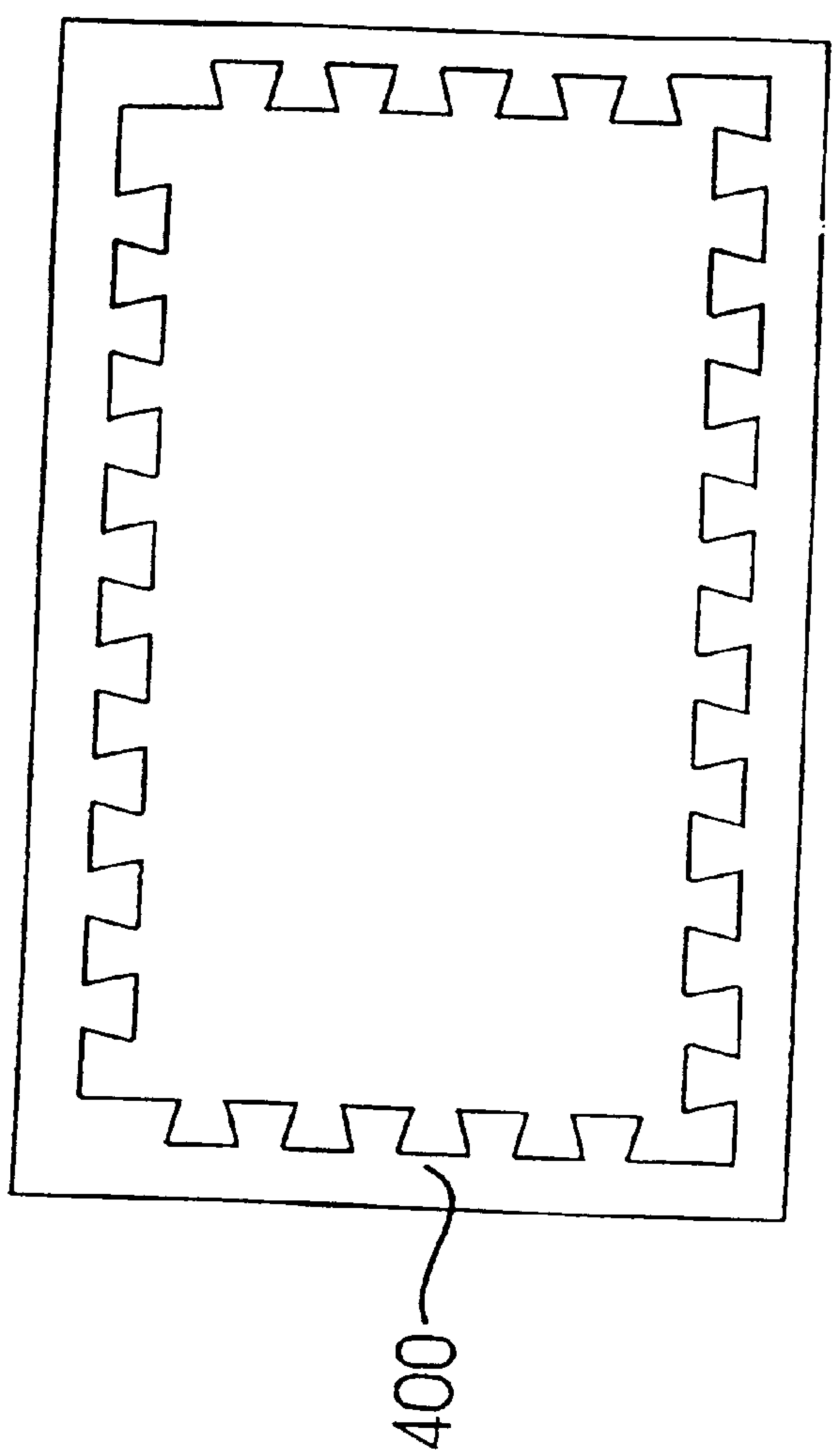

Fig. 30

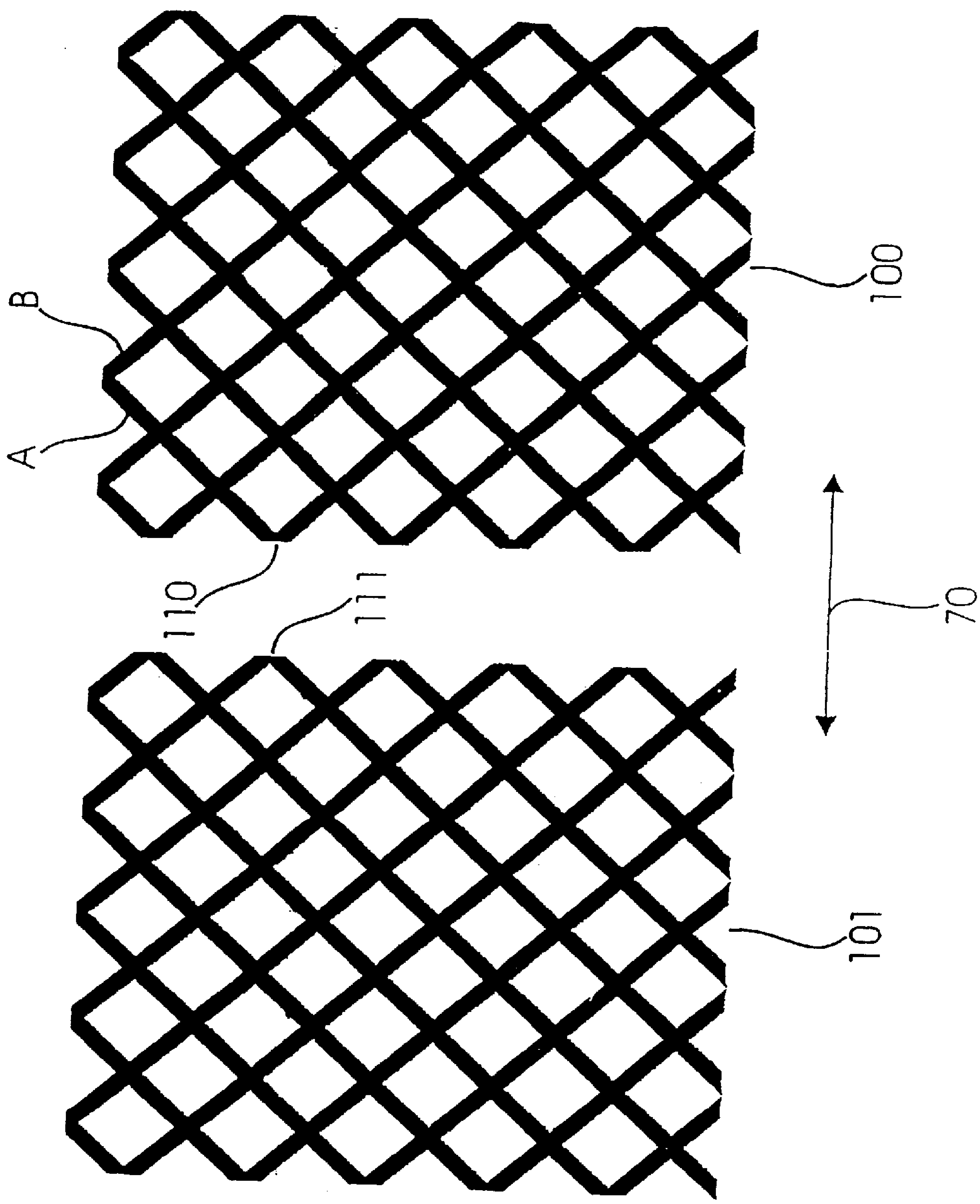

Fig. 31

TWO-DIMENSIONAL, ANTI-SCATTER GRID AND COLLIMATOR DESIGNS, AND ITS MOTION, FABRICATION AND ASSEMBLY

This is a continuation-in-part of U.S. patent application Ser. No. 09/373,972, filed on Aug. 16, 1999 now abandoned, which is a continuation of U.S. patent application Ser. No. 08/879,258, filed on Jun. 19, 1997, now U.S. Pat. No. 5,949,850, the entire contents of each of said prior applications being expressly incorporated herein by reference.

The invention was made with Government support under Grant Number 1 R43 CA76752-01 awarded by the National Institutes of Health, National Cancer Institute. The Government has certain rights in the invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a method and apparatus for making focused and unfocused grids and collimators which are movable to avoid grid shadows on an imager, and which are adaptable for use in a wide range of electromagnetic radiation applications, such as x-ray and gamma-ray imaging devices and the like. More particularly, the present invention relates to a method and apparatus for making focused and unfocused grids, such as air core grids, that can be constructed with a very high aspect ratio, which is defined as the ratio between the height of each absorbing grid wall and the thickness of the absorbing grid wall, and that are capable of permitting large primary radiation transmission therethrough.

2. Description of the Related Art

Anti-scatter grids and collimators can be used to eliminate the scattering of radiation to unintended and undesirable directions. Radiation with wavelengths shorter than or equal to soft x-rays can penetrate materials. The radiation decay length in the material decreases as the atomic number of the grid material increases or as the wavelength of the radiation increases. These grid walls, also called the septa and lamellae, can be used to reduce scattered radiation in ultraviolet, x-ray and gamma ray systems, for example. The grids can also be used as collimators, x-ray masks, and so on.

For scatter reduction applications, the grid walls preferably should be two-dimensional to eliminate scatter from all directions. For many applications, the x-ray source is a point source close to the imager. An anti-scatter grid preferably should also be focused. Methods for fabricating and assembling focused and unfocused two-dimensional grids are described in U.S. Pat. No. 5,949,850, entitled "A Method and Apparatus for Making Large Area Two-dimensional Grids", referenced above.

When an anti-scatter grid is stationary during the acquisition of the image, the shadow of the anti-scatter grid will be cast on the imager, such as film or electronic digital detector, along with the image of the object. It is undesirable to have the grid shadow show artificial patterns.

The typical solution to eliminating the non-uniform shadow of the grid is to move the grid during the exposure. The ideal anti-scatter grid with motion will produce uniform exposure on the imager in the absence of any objects being imaged.

One-dimensional grids, also known as linear grids and composed of highly absorbing strips and highly transmitting interspaces which are parallel in their longitudinal direction, can be moved in a steady manner in one direction or in an oscillatory manner in the plane of the grid in the direction perpendicular to the parallel strips of highly absorbing lamellae. For two-dimensional grids, the motion can either be in one direction or oscillatory in the plane of the grid, but the grid shape needs to be chosen based on specific criteria.

The following discussion pertains to a two-dimensional grid with regular square patterns in the x-y plane, with the grid walls lined up in the x-direction and y-direction. If the grid is moving at a uniform speed in the x-direction, the film will show unexposed stripes along the x-direction, which also repeat periodically in the y-direction. The width of the unexposed strips is the same or essentially the same as the thickness of the grid walls. This grid pattern and the associated motion are unacceptable.

If the grid is moving at a uniform speed in the plane of the grid, but at a 45 degree angle from the x-axis, the image on the film or imager is significantly improved. However, strips of slightly overexposed film parallel to the direction of the motion at the intersection of the grid walls will still be present. As the grid moves in the x-direction at a uniform speed, the grid walls block the x-rays everywhere, except at the wall intersection, for the fraction of the time

$$2d/D,$$

where d is the thickness of the grid walls and D is the periodicity of the grid walls. At the wall intersection, the grid walls blocks the x-rays for the fraction of the time

$$2d/D<t\leqq d/D,$$

depending on the location. Thus, stripes of slightly overexposed x-ray film are produced.

Methods for attempting to eliminate the overexposed strips discussed above are disclosed in U.S. Pat. Nos. 5,606,589, 5,729,585 and 5,814,235 to Pellegrino et al., the entire contents of each patent being incorporated herein by reference. These methods attempt to eliminate the overexposed strips by rotating the grid by an angle A, where A=atan(n/m), and m and n are integers. However, these methods are unacceptable or not ideal for many applications.

Accordingly, a need exists for a method and apparatus for eliminating the overexposed strips associated with two-dimensional focused or unfocused grid intersections.

SUMMARY OF THE INVENTION

An object of the present invention, therefore, is to provide a method and apparatus for manufacturing a focused or unfocused grid which is configured to minimize overexposure at its wall intersections when the grid is moved during imaging.

Another object of the present invention is to provide a method and apparatus for moving a focused or unfocused grid so that no perceptible areas of variable density are cast by the grid onto the film or other two-dimensional electronic detectors.

A further object of the present invention is to provide a method and apparatus for assembling sections of a two-dimensional, focused or unfocused grid.

Still another object of the present invention is to provide a method and apparatus for joining stacked layers of two-dimensional focused or unfocused grids.

These and other objects of the present invention are substantially achieved by providing a grid, adaptable for use with electromagnetic energy emitting devices, comprising at least metal layer, formed by electroplating. The grid comprises top and bottom surfaces, and a plurality of solid integrated walls. Each of the solid integrated walls extends from the top to bottom surface and having a plurality of side surfaces. The side surfaces of the solid integrated walls are arranged to define a plurality of openings extending entirely through the layer. For some applications, all the walls are 90° with respect to the top and bottom surfaces. For some other applications, at least some of the walls extend at an angle other than 90° with respect to the top and bottom surfaces such that the directions in which the walls extend all converge at a point in space at a predetermined distance from the front surface of the at least one layer.

These and other objects of the present invention are also substantially achieved by providing a grid, adaptable for use with electromagnetic energy emitting devices. The grid comprises at least one solid metal layer, formed by electroplating. The solid metal layer comprises top and bottom surfaces, and a plurality of solid integrated, intersecting walls, each of which extending from the top to bottom surface and having a plurality of side surfaces. The side surfaces of the walls are arranged to define a plurality of openings extending entirely through the layer, and at least some of the side surfaces have projections extending into respective ones of the openings.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features and advantages of the present invention will be more readily apprehended from the following detailed description when read in connection with the appended drawings, in which:

FIG. **1** shows a section of a focused stationary grid according to an embodiment of the present invention, in which the grid openings are focused to a point x-ray source;

FIG. **2***a* is a schematic of the grid shown in FIG. **1** rotated an angle of 45 degrees with respect to the x and y axes, and being positioned so that the central ray emanates from point x-ray source onto the edge of the grid;

FIG. **2***b* is a schematic of the grid shown in FIG. **1** rotated at an angle of 45 degrees with respect to the x and y axes, and being positioned so that the central ray emanates from point x-ray source onto the center of the grid;

FIG. **3** is an example of a top view of a grid layout as shown in FIG. **1**, modified and positioned so that one set of grid walls are perpendicular to a direction of motion along the x-axis and the other set of grid walls is at an angle 0 with respect to the direction of motion, thus forming a parallelogram grid pattern applicable for linear grid motion;

FIG. **4** is an example of a top view of a grid layout as shown in FIG. **1**, modified and positioned so that one set of grid walls is perpendicular to the direction of motion along the x-axis and the other set of grid walls makes an angle 0 with respect to the direction of motion, thus forming another parallelogram grid pattern applicable for linear grid motion;

FIG. **5** is an example of a top view of a grid layout as shown in FIG. **1**, modified so that the angle of the grid walls are neither parallel nor perpendicular to the direction of grid motion along the x-axis, thus forming a further parallelogram grid pattern applicable for linear grid motion;

FIG. **6** is a variation of the grid pattern shown in FIG. **5**, in which the grid openings are rectangular;

FIG. **7** is a variation of the grid pattern shown in FIG. **5** in which the grid openings are squares;

FIG. **8** is a variation of the grid pattern shown in FIG. **5** having modified corners at the wall intersections according to an embodiment of the present invention for eliminating artificial images or shadows on the imager along the direction of linear motion of the grid;

FIG. **9** is the top view of only the additional grid areas that were added to a square grid shown in FIG. **7** to form the grid pattern shown in FIG. **8**;

FIG. **10** is the top view of a grid with modified corners at the wall intersections according to another embodiment of the present invention for eliminating artificial images or shadows on the imager along the direction of linear motion of the grid;

FIG. **11** is a top view of only the additional grid areas that were added to a square grid shown in FIG. **7** to form the grid pattern shown in FIG. **10**;

FIG. **12** is a detailed view of a wall intersection of the grid illustrating a general arrangement of an additional grid area that is added to the wall intersection of the grid;

FIG. **13** is a detailed view of a wall intersection of the grid illustrating a general arrangement of an additional grid area that is added to the wall intersection of the grid;

FIG. **14** is a detailed view of a wall intersection of another grid according to an embodiment of the present invention, illustrating a general arrangement of an additional grid area that is added proximate to the wall intersection and not connected to any of the grid walls;

FIG. **15** is a detailed view of a wall intersection of another grid according to an embodiment of the present invention, illustrating a general arrangement of an additional grid area that is added to the wall intersection of the grid, such that two rectangular or substantially rectangular pieces are placed at opposing (non-adjacent) left and right comers of the wall intersection;

FIG. **16** is a detailed view of a wall intersection of another grid according to an embodiment of the present invention, illustrating a general arrangement of an additional grid area that is added to the wall intersection of the grid, such that two trapezoidal pieces are placed at opposing (non-adjacent) left and right comers of the wall intersection;

FIG. **17** shows a top view of a portion of a grid according to an embodiment of the present invention, having more than one type of modified corner as shown in FIGS. **12–16**;

FIG. **18** shows one layer of grid to be assembled from two sections and their joints, using the pattern as shown in FIG. **7**;

FIG. **19** shows the location of the imaginary central ray and reference lines for photoresists exposures using the grid shape of FIG. **4**;

FIGS. **20***a* and **20***b* illustrate exemplary patterns of x-ray masks used to form the grid pattern shown in FIG. **19** according to an embodiment of the present invention;

FIGS. **21***a* and **21***b* show an exposure method according to an embodiment of the present invention which uses sheet x-ray beams, such that FIG. **21***a* shows the cross-section in the plane of the sheet x-ray beam and FIG. **21***b* shows the cross-section perpendicular to the sheet x-ray beam, and the x-ray mask and the substrate are tilted with respect to the sheet x-ray beam to form the focusing effect of the grid;

FIG. **21***c* shows another exposure method according to an embodiment of the present invention which uses sheet x-ray beams to form the focusing effect of the grid;

FIG. **22** shows an exposure method according to an embodiment of the present invention which is used in place of the method shown in FIG. **21***b* for exposing grids or portions of grids where the walls, joints or holes are not focused;

FIG. **23** shows an example the top and bottom patterns of the exposed photoresists exposed according to the methods shown in FIGS. **21***a* and **21***b;*

FIG. **24** shows an example of the top and bottom patterns of an incorrectly exposed photoresists which was exposed using only two masks and a sheet x-ray beam;

FIGS. **25***a* and **25***b* show an example of x-ray masks used to expose the central portion of right-hand-side of a focused grid shown in FIG. **18** using a sheet x-ray beam according to an embodiment of the present invention;

FIG. **25***c* shows an example of an x-ray mask used to expose the grid edge joints of the right-hand-side of a focused grid shown in FIG. **18** using a sheet x-ray beam according to an embodiment of the present invention;

FIG. **26** shows a portion of the grid including the left joining edge and a wide border;

FIG. **27** shows an example of an x-ray mask used to expose the grid edge joint and the border of FIG. **26**, which is in addition to the masks already shown in FIGS. **25***a* and **25***b,* according to an embodiment of the present invention;

FIGS. **28***a* and **28***b* show an example of an x-ray masks used to expose the photoresist for the focused grids shown in FIGS. **7**, **8**, **10** or **17** using a sheet x-ray beam according to an embodiment of the present invention;

FIG. **28***c* shows an example of an x-ray mask required to expose the additional grid structure for linear motion according to an embodiment of the present invention;

FIG. **29** is a side view of an example of a grid including a frame according to an embodiment of the present invention;

FIG. **30** illustrates a top view of the frame shown in FIG. **29**, less the grid layers; and

FIG. **31** illustrates pieces of a grid layer that can be assembled in the frame shown in FIGS. **29** and **30**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention provides a method and apparatus for making large area, two-dimensional, high aspect ratio, focused or unfocused x-ray anti-scatter grids, anti-scatter grid/scintillators, x-ray filters, and the like, as well as similar methods and apparatus for ultraviolet and gamma-ray applications. Referring now to the drawings, FIG. **1** shows a schematic of a section of a two-dimensional, focused anti-scatter grid **30** produced by a method of grid manufacture according to an embodiment of the present invention, as described in more detail in U.S. Pat. No. 5,949,850 referenced above.

The object to be imaged (not shown) is positioned between the x-ray source and the x-ray grid **30**. The grid openings **31** which are defined by walls **32** are square in this example. However, the grid openings can be any practical shape as would be appreciated by one skilled in the methods of grid construction. The walls **32** are uniformly thick or substantially uniformly thick around each opening in this figure, but can vary in thickness as desired. The walls **32** are slanted at the same angle as the angle of the x-rays emanating from the point source, in order for the x-rays to propagate through the holes to the imager without significant loss. This angle increases for grid walls further away from the x-ray point source. In other words, an imaginary line extending from each grid wall **32** along the x-axis **40** could intersect the x-ray point source. A similar scenario exists for the grid walls **32** along the y-axis **50**.

As shown, the x-ray propagates out of a point source **61** with a conical spread **60**. The x-ray imager **62**, which may be an electronic detector or x-ray film, for example, is placed adjacent and parallel or substantially parallel to the bottom surface of the x-ray grid **30** with the x-ray grid between the x-ray source **61** and the x-ray imager. Typically, the top surface of the x-ray grid **30** is perpendicular or substantially perpendicular to the line **63** that extends between the x-ray source and the x-ray grid **30**.

To facilitate the description below, a coordinate system in which the grid **30** is omitted will now be defined. The z-axis is line **63**, which is perpendicular or substantially perpendicular to the anti-scatter grid, and intersects the point x-ray source **61**. The z=0 coordinate is defined as the top surface of the anti-scatter grid. As further shown, the central ray **63** propagates to the center of the grid **30**, which is marked by a virtual "+" sign **64**.

FIGS. **2***a* and **2***b* show schematics of two air-core x-ray anti-scatter grids, such as grid **30** shown in FIG. **1**, which are stacked on top of each other in a manner described in more detail below to form a grid assembly. These layers of the grid walls can achieve high aspect ratio such that they are structurally rigid. The stacked grids **30** can be moved steadily along a straight line (e.g., the x-axis **40**) during imaging. As shown in these figures, the grids **30** have been oriented so that their walls extend at an angle of 45° or about 45° with respect to the x-axis **50**. The top surface of the top grid **30** is in the x-y plane.

The central ray **63** from the x-ray source **61** is perpendicular or substantially perpendicular to the top surface of the top grid **30**. For mammographic applications, the central ray **63** propagates to the top grid **30** next to the chest wall at the edge or close to the edge of the grid on the x-axis **40**, which is marked as location **65** in FIG. **2***a*. For general radiology, the central ray **63** is usually at the center of the top grid **30**, which is marked as location **64** in FIG. **2***b*. In this example, the line of motion **70** of the grid assembly is parallel or substantially parallel to the x-axis **40**. In the x-y plane, one set of the walls **32** (i.e., the septa) is at 45° with respect to the line of motion **70**, and the shape of the grid openings **31** is nearly square. The grid assembly can move in just one direction or it can move in both directions in the x-y plane. During motion, the speed at which the grid moves should be constant or substantially constant.

Two categories of grid patterns can be used with linear grid motion to eliminate non-uniform shadow of the grid. The description below pertains to portions of the grid not at the edges of the grid, so the border is not shown. For illustration purposes only, the dimensions of the drawings are not to scale, nor have they been optimized for specific applications.

I. Grid Design Art Type I for Linear Motion

As discussed above, the present invention provides a two-dimensional grid design and a method for moving the grid so that the image taken will leave no substantial artificial images for either focused or unfocused grids for some applications. In particular, as will now be described, the present invention provides methods for constructing grid designs that do not have square patterns. The rules of construction for these grids are discussed below.

Essentially, Type I methods for eliminating grid shadows produced by the intersection of the grid walls are based on the assumptions that: (1) there is image blurring during the conversion of x-rays to visible photons or to electrical charge; and/or (2) the resolution of the imaging device is low. A general method of grid design provides a grid pattern that is periodic in both parallel and perpendicular (or substantially parallel and perpendicular) directions to the direction of motion. The construction rules for the different grid variations are discussed below.

Grid Design Variation I.1: A Set of Parallel Grid Walls Perpendicular to the Line of Motion

FIG. **3** shows a top view of an exemplary grid layout that can be employed in a grid **30** as discussed above. The grid layout consists of a set of grid walls, A, that are perpendicular or substantially perpendicular to the direction of motion, and a set of grid walls, B, intersecting A. The thicknesses of grid walls A and B are a and b, respectively. The thicknesses a and b are equal in this figure, but they are not required to be equal. The angle θ is defined as the angle of the grid wall B with respect to the x-axis. The grid moves in the x-direction as indicated by **70**. P_x and P_y are the periodicities of the intercepting grid wall pattern in the x- and y-directions, respectively. D_x and D_y represent the pitch of grid cells in the x- and y-directions, respectively.

The periodicity of the grid pattern in the x-direction is $P_x=MD_x$, where M is a positive integer greater than 1. The periodicity of the grid pattern in the y-direction is $P_y=M(D_y/N)$, where N is a positive integer greater than or equal to 1, M≠N and $P_y=|\tan(\theta)|P_x$. For linear motion, the grid pattern can be generated given D_x, (θ or D_y), (M or P_x) and (N or P_y). The parameter range for the angle θ is $0°<|\theta|<90°$. The best values for the angle θ are away from the two end limits, 0° and 90°. The grid intersections are spaced at intervals of P_y/M in the y-direction.

If D_x, θ, M and N are given, the parameters P_x, P_y, and D_y can be calculated FIG. **3** is a plot of a section of the grid for the following chosen parameters: θ=45°, M=3 and N=1.

If the parameters D_x, D_y, M and N are chosen, the angle θ, P_x and P_y can be calculated: $P_x=MD_x$, $P_y=ND_y$ and $\theta=\pm\text{atan}(P_y/P_x)$. FIG. **4** is a plot of a section of the grid for the parameters N=2, M=7 and $\theta=-\text{atan}(2D_y/7D_x)$.

Grid Design Variation I.2: Grid Walls Not Perpendicular to the Line of Motion

FIG. **5** is the top view of a section of the grid layout where neither grid walls A nor B are perpendicular to the direction of linear motion. The thicknesses of grid walls A and B are a and b, respectively. The thicknesses a and b are equal in this figure, but they are not required to be. The angles between the grid walls A and B relative to the x-axis are ϕ and θ, respectively. Choosing D_x, (M or P_x), (N or P_y), and angles (θ or D_y) and ϕ, then $P_y=|\tan(\theta)|P_x$, $N=P_y/D_y$ and $(M=P_x/D_x)$. The centers of grid intersections are separated by a distance P_y/M in the y-direction. FIG. **5** shows an example where θ=−15°, ϕ=−80°, M=5 and N=1.

FIG. **6** is the top view of a section of the grid layout where neither grid walls A or B are perpendicular to the direction of motion, but grid wall A is perpendicular to grid wall B, thus a special case of FIG. **5**, where the grid openings are rectangular. The thicknesses of grid walls A and B are a and b, respectively. The thicknesses are equal in this figure, but again, they are not required to be equal. The angles between the grid walls A and B relative to the x-axis are ϕ and θ, respectively. By choosing D_x, (M or P_x), (N or D_y), (θ or P_y) and ϕ, then $P_y=|\tan(\theta)|P_x$, $P_y=ND_y$, and $P_x=MD_x$. The centers of grid intersections are separated by a distance P_y/M in the y-direction. FIG. **6** shows an example where θ=10°, ϕ=−80°, M=10 and N=1.

Comments on the Grid Motion Associated with Grid Design I

For all grid layout methods, the range of parameters for the grid can vary depending on many factors, such as film versus digital detectors, the type of phosphor used in film, the type of application, and whether there is direct x-ray conversion or indirect x-ray conversion, etc. The ultimate criteria are that the overexposed strip caused by grid intersections is close enough to each other so that they do not appear in the imaging system.

Some general conditions can be given for the range of parameters for Grid Design Type I and associated motion. It is better for grid openings to be greater than the grid wall thicknesses a and b. For film, P_y/M should be smaller than the x-ray to optical radiation conversion blurring effect produced by the phosphor. For digital imagers with direct x-ray conversion, it is preferable that pixel pitch in the y-direction is an integer multiple of the spacing, P_y/M. Otherwise, the grid shadows will be unevenly distributed on the pixels.

The distance of linear travel, L, of the grid during the exposure should be many times the distance P_x, where $kP_x>L>(kP_x-\delta L)$, $D_x>\delta L>\alpha\sin(\phi)$, $D_x>\delta L>b/\sin(\theta)$ $\delta L/P_x<<1$, k?1, and k is an integer. The ratio of δL/L should be small to minimize the effect of shadows caused by the start and stop. The distance L can be traversed in a steady motion in one direction if it is not too long to affect the transmission of primary radiation. Assuming that the x-ray beam is uniform over time, the speed the grid traverses the distance L should be constant, but the direction can change. In general, the speed at which the grid moves should be proportional to the power of the x-ray source. If the distance L to be traveled in any one direction at the desired speed is too long, causing reduction of primary radiation, then it can be traversed by steady linear motion that reverses direction.

II. Grid Design Type II for Linear Motion

The present invention provides other two-dimensional grid designs and methods of moving the grid such that the x-ray image will have no overexposed strips at the intersection of the grid walls A and B. The principle is based on adding additional cross-sectional areas to the grid to adjust for the increase of the primary radiation caused by the overlapping of the grid walls. This grid design and construction provides uniform x-ray exposure.

Two illustrations of the concept are given below, followed by the generalized construction rules. This grid design is feasible for the SLIGA fabrication method described in U.S. Pat. No. 5,949,850 referenced above, because x-ray lithography is accurate to a fraction of a micron even for a thick photoresist.

Grid Design Variation II.1: Square Grid Shape with an Additional Square Piece

FIG. **7** shows a section of a square patterned grid with uniform grid wall thickness a and b rotated at a 45° angle with respect to the direction of motion. When square pieces in the shape of the septa intersection are added to the grid next to the intersection, with one per intersection as shown in FIG. **8**, the grid walls leave no shadow for a grid moving with linear motion **70**. In the FIG. **8**, $D_x=D_y=P_x=P_y$ and θ=45°. The additional grid area is shown alone in FIG. **9**.

Grid Design Variation II.2: Square Grid Shape with Two Additional Triangular Pieces

FIG. **10** shows another grid pattern, which has the same or essentially the same effect as the grid pattern in FIG. **8**, by placing two additional triangular pieces at opposite sides of intersecting grid walls. In this FIG. **10** example, $D_x=D_y=P_x=P_y$ and θ=45°. The additional grid area is shown alone in FIG. **11**.

With these modified corners added to the grid, there will not be any artificial patterns as the grid is moved in a straight line as indicated by **70** for a distance L, where $kD_x > L \geqq (kD_x - \delta L)$, $D_x >> \delta L > s$, $\delta L << L$, $k >> 1$ and k is an integer. Along the x-axis, the grid wall thickness is s and the periodicity of the grid is $P_x = D_x$. The distance of linear travel L should be as large as it can be while keeping the maximum transmission of primary radiation. The condition for linear grid motion in just one direction is easier for grid Design Type II to achieve than grid Design Type I or the designs in U.S. Patents by Pellegrino et al., because $P_x > D_x$ for grid Design Type I.

General Construction Methods for Quadrilateral Grid Design Type II for Linear Motion

The exact technique for eliminating the effect of slight overexposure caused by the intersection of the grid walls with linear motion is to add additional grid area at each corner. Two special examples are shown in FIGS. **8** and **10** discussed above, and the general concept is described below and illustrated in FIGS. **12–16**. The general rule is that the overlapping grid region C formed by grid walls A and B has to be "added back" to the grid intersecting region, so that the total amount of the wall material of the grid intersected by a line propagating along the x-direction remains constant at any point along the y axis. In other words, the total amount of wall material of the grid intersected by a line propagating in a direction parallel to the x-axis along the edge of a grid of the type shown, for example, in FIGS. **8** or **10**, is identical to the amount of wall material of the grid intersected by a line propagating in a direction parallel to the x-axis through any position, for example, the center of the grid.

This concept can be applied to any grid layout that is constructed with intersecting grid walls A and B. The widths of the intersecting grid walls do not have to be the same and the intersections do not have to be at 90°, but grid lines cannot be parallel to the x-axis. The width of the parallel walls B do not have to be identical to each other, nor do they need to be equidistant from one another, but they do have to be periodic along the x-axis with period P_x. The widths of the parallel lines A do not have to be identical to each other, nor do they need to be equidistant from one another, but they do have to be periodic along the y-axis with period P_y. The generalized construction rules are described using a single intersecting corner of walls A and B for illustration as shown in FIGS. **12–16**. The top and bottom corners of parallelogram C are both designated as γ and the right and left corners of the parallelogram C as $\beta 1$ and $\beta 2$, respectively. Dashed lines, f, parallel to the x-axis, the direction of motion, are placed through points γ. The points where the dashed lines f intersect the edges of the grid lines are designated as $\alpha 1$, $\alpha 2$, $\alpha 3$ and $\alpha 4$.

FIG. **12** shows the addition to the grid in the form of a parallelogram F formed by three predefined points: $\alpha 1$, $\alpha 2$, $\beta 1$, and δ , where δ is the fourth corner. This is the construction method used for the grid pattern shown in FIG. **8**.

FIG. **13** shows the addition of the grid area in the shape of two triangles, E1 and E2, formed by connecting the points $\alpha 1$, $\alpha 2$, $\beta 1$ and $\alpha 3$, $\alpha 4$, $\beta 2$, respectively. This is the construction method used to make the grid pattern shown in FIG. **10**. There are an unlimited variety of shapes that would produce uniform exposure for linear motion. Samples of three other alternatives are shown in FIGS. **14–16**. They produce uniform exposure because they satisfy the criteria that the lengths through the grid in the x-direction for any value y are identical. There is no or essentially no difference in performance of the grids if motion is implemented correctly. Additional grid areas of different designs can be mixed on any one grid without visible effect when steady linear motion is implemented. FIG. **17**, for example, illustrates and arrangement where different combinations of grid corners are implemented in one grid. However, the choice of grid comers depends on the ease of implementation and practicality. Also, since it is desirable for the transmission of primary radiation to be as large as possible, the grid walls occupy only a small percentage of the cross-sectional area.

General Construction Methods for Grid Design Type II for Linear Grid Motion

It should be first noted that this concept does not limit grid openings to quadrilaterals. Rather, the grid opening shapes could be a wide range of shapes, as long as they are periodic in both x and y directions. The grid wall intercepts do not have to be defined by four straight line segments. Artificial non-uniform shadow will not be introduced as long as the length of the lines through the grid in the x-direction are identical through any y coordinate. In addition to adding the corner pieces, the width of some sections of the grid walls would have to be adjusted for generalized grid openings.

However, not every grid shape that is combined with steady linear motion produces uniform exposure without artificial images. The desirable grid patterns that produce uniform exposure have to satisfy, at a minimum, the following criteria:

- The grid pattern has to be periodic in the direction of motion with periodicity P_x.
- No segment of the grid wall is primarily along the direction of the grid motion.
- The grid walls block the x-ray everywhere for the same fraction of the time per spatial period P_x at any position perpendicular to the direction of motion.
- The grid walls do not have to have the same thickness.
- The grid patterns are not limited to quadrilaterals.
- These grid patterns have to be coupled with a steady linear motion such that the distance of the grid motion, L, satisfies the condition described in Sections Grid Design Type I and Type II for Linear Motion.
- If the walls are not continuous at the intersection or not identical in thickness through the intersection, the construction rule that must be maintained is that the length of the line through the grid in the x-direction is identical through any y-coordinate. Hexagons with modified corners are examples in this category.

Implementation of the Grid Design Type II for Linear Grid Motion

The additional grid area at the grid wall intersections can be implemented in a number of ways for focused or unfocused grids to obtain uniform exposure. The discussion will use FIGS. **8** and **10** as examples.

1. The grid patterns with the additional grid area, such as FIGS. **8**, **10**, **17**, and so on, may have approximately the same cross-sectional pattern along the z-axis.
2. Since the additional pieces of the grid are for the adjustment of the primary radiation, these additional grid areas in FIGS. **8**, **10**, **17**, and so on, only have to be high enough to block the primary radiation. This allows new alternatives in implementation.
   - A portion of the grid layer need to have the additional grid area, while the rest of the grid layer do not. For example, a layer of the grid is made with pattern shown in FIG. **8**, while the other layers can have the pattern shown in FIG. **7**.
   - The portion of the grid with the shapes shown in FIGS. **8**, **10**, **17**, and so on, can be released from the

substrate for assembly or attached to a low atomic weight substrate.

The portion of the grid with the pattern shown in FIGS. **8**, **10**, **17**, and so on, can be made from materials different from the rest of the grid. For example, these layers can be made of higher atomic weight materials, while the rest of the grid can be made from fast electroplating material such as nickel. The high atomic weight material allows these parts to be thinner than if nickel were used. For gold, the height of the grid can be 20 to 50 μm for mammographic applications. The height of the additional grid areas depends on the x-ray energy, the grid material, the application and the tolerances for the transmission of primary radiation.

The photoresist can be left in the grid openings to provide structure support, with little adverse impact on the transmission of primary radiation.

3. The additional grid areas shown in FIGS. **9**, **11**, and so on, can be fabricated separately from the rest of the grid.

These areas can be fabricated on a low atomic weight substrate and remain attached to the substrate.

These areas can be fabricated along with the assembly posts, which are exemplified in FIGS. **16***a* and **16***b* of U.S. Pat. No. 5,949,850, referenced above.

Patterns shown in FIGS. **9**, **11**, and so on, can be made of a material different from the rest of the grid. For example, these layers can be made from materials with higher atomic weight, while the rest of the grid can be made of nickel. The high atomic weight material allows these parts to be thinner than if nickel were used. For gold, the height of the grid can be 20 to 100 μm for mammographic applications. The height of the additional grid areas depends on the x-ray energy, the grid material, the application and the tolerances for the transmission of primary radiation.

The photoresist can be left on for low atomic weight substrate to provide structure support with little adverse impact on the transmission of primary radiation.

Grid Parameters and Design

Examples of the parameter range for mammography application and definitions are given below. Grid Pitch is P_x. Aspect Ratio is the ratio between the height of the absorbing grid wall and the thickness of the absorbing grid wall. Grid Ratio is the ratio between the height of the absorbing wall including all layers and the distance between the absorbing walls.

	Range	Best case
Grid Type	Type I or II	Type II/FIG. 10
Grid Opening Shape	Quadrilateral	Square
Thickness of Absorbing Wall on the top plane of the grid	10 μm–200 μm	≈20 μm
Grid Pitch for Type I	1000 μm–5000 μm	
Grid Pitch for Type II	100 μm–2000 μm	≈300 μm
Aspect Ratio for a Layer	1–100	>15
Number of Layers	2–100	2–7
Grid Ratio	3–10	5–8

However, it should be noted that different parameter ranges are used for different applications, and for different radiation wavelengths.

III. Grid Joint Design

Designs of grid joints were described in U.S. Pat. No. 5,949,850, referenced. FIG. **18** shows a grid to be assembled from two sections, using the pattern of FIG. **7** as an example. The curved corner interlocks in the shape of **110** and **111** shown in FIG. **18** are found to be more desirable structurally than other grid joints. The details of the corner can vary depending on the implementation of the additional grid structure with motion.

IV. Grid Fabrication

Unfocused grids of any design can be easily fabricated with one mask and a sheet x-ray beam.

When grid size is too large to be made in one piece, sections of grid parts can be made and assembled from a collection of grid pieces. Grids with high grid ratios can be obtained by stacking if they cannot be made the desired thickness in one layer.

Focused grids of any pattern can be fabricated by the method described in U.S. Pat. No. 5,949,850, referenced above. For focused grids, methods for exposing the photoresist using a sheet of parallel x-ray beams are described below.

Grid Design Type I For Linear Motion and Single Piece

If the pattern of the grid in the x-y plane can be made in one piece (not including the border and other assembly parts), the easiest method is to expose the photoresist twice with two masks. The pattern of FIG. **4** is used as an example to assist in the explanation below. This method can be applied to any grid patterns with quadrilateral shapes formed by two intersecting sets of parallel lines.

1. For exemplary purposes, the case where the central ray is located at the center of the grid, as shown in FIG. **19**, which is marked by a virtual "+" sign **100**, will be considered. Two imaginary reference lines **101** are drawn running through the "+" sign, parallel to grid walls A and B.
2. The grid pattern is to be produced by two separate masks. The desired patterns for the two masks are shown in FIG. **20***a* and **20***b*.
3. The photoresist exposure procedure by the sheet x-ray beam is shown in FIGS. **21***a* and **21***b*. For the first exposure, an x-ray mask **730**, with pattern shown in FIG. **20***a* or **20***b*, is placed on top of the photoresist **710** and properly aligned, as follows. In FIG. **21***a*, the sheet x-ray beam **700** is oriented in the same plane as the paper, and the reference lines **101** in FIGS. **20***a* or **20***b* of the x-ray masks **730** are parallel to the sheet x-ray beam **700**. In FIG. **21***b*, the sheet x-ray beam **700** is oriented perpendicular to the plane of the paper, as are the reference lines of x-ray mask **730**. The x-ray mask **730**, photoresist **710**, and substrate **720** form an assembly **750**. The assembly **750** is positioned in such a way that the line **740** that connects the virtual "+" sign **100** with the virtual point x-ray source **62** is perpendicular to the photoresist **710**. The angle α is 0° when the reference line **101** is in the plane of the x-ray source **700**. To obtain the focusing effect in the photoresist **710** by the sheet x-ray beam **700**, the assembly **750** rotates around the virtual point x-ray source **62** in a circular arc **760**. This method will produce focused grids with opening that are focused to a virtual point above the substrate.

There are situations that one would like to produce a layer of the grid with that are focused to a virtual point below the substrate as shown in FIG. **21***c*. In FIG. **21***c*, the sheet x-ray beam **700** is oriented perpendicular to the plane of the paper, as are the reference lines of x-ray mask **730**. The assembly

750 is positioned in such a way that the line **740** that connects the virtual "+" sign **100** with the virtual point x-ray source **62** is perpendicular to the photoresist **710**. The angle α is 0° when the reference line **101** is in the plane of the x-ray source **700**. To obtain the focusing effect in the photoresist **710** by the sheet x-ray beam **700**, the assembly **750** rotates around the virtual point x-ray source **62** in a circular arc **770**.

4. For the second exposure, the second x-ray mask is properly aligned with the photoresist **710** and the substrate **720**. The exposure method is the same as in FIGS. **21***a* and **21***b* or **21***c*.
5. To facilitate assembly, a border is desirable. The border can be part of FIGS. **20***a* or **20***b;* or it can use a third mask. The grid border mask should be aligned with the photoresist **710** and its exposure consists of moving the assembly **750** such that the sheet x-ray beam **700** always remains perpendicular to the photoresist **710**, as shown in FIG. **22**. The assembly **750** moves along a direction **780**.
6. The rest of the fabrication steps are the same as in described in U.S. Pat. No. 5,949,850, referenced above.

Grid Design Type I For Linear Motion and Multiple Pieces Joint Together per Layer

If two or more pieces of the grid are required to make a large grid, the grid exposure becomes more complicated. In that case, at least three masks will be required to obtain precise alignment of grid pieces.

The desired exposure of the photoresist is shown in FIG. **23**, using pattern **1 15** shown on the right-hand-side of FIG. **18** as an example. The effect of the exposure on the photoresist outside the dashed lines **202** is not shown. The desirable exposure patterns are the black lines **120** for one surface of the photoresist, and are the dotted lines **130** for the other surface. The location of the central x-ray is marked by the virtual "+" sign at **200**. The shape of the left border is preserved and all locations of the grid wall are exposed.

Although the procedures discussed above with regard to FIGS. **21***a* and **21***b* are generally sufficient to obtain the correct exposure near the grid joint using two masks, one for wall A and one for wall B, incorrect exposure may occur from time to time. This problem is illustrated in FIG. **24**. The masks are made so as to obtain correct photoresist exposure at the surface of the photoresist next to the mask. The dotted lines **130** denote the pattern of the exposure on the other surface of the photoresist. Some portions of the photoresist will not be exposed **140**, but other portions that are exposed **141** should not be. The effect of the exposure on the photoresist outside the dashed lines **202** is not shown.

At least three x-ray masks are required to alleviate this problem and obtain the correct exposure. Each edge joint boundary needs a mask of its own. These are shown in FIGS. **25***a*–**25***c*. FIG. **25***a* shows a portion of the grid lines B as lines **150**, which do not extend all the way to the grid joint boundary on the left. FIG. **25***b* shows a portion of the grid lines A as items **160**, which do not extend all the way to the grid joint boundary on the left. FIG. **25***c* shows the mask for the grid joint boundary on the left. The virtual "+" **200** shows the location of the central ray **63** in FIGS. **25***a*–**25***c*. The distances from the joint border to be covered by each mask depend on the grid dimensions, the intended grid height, and the angle.

The exposures of the photoresist **710** by all three masks shown in FIGS. **25***a*–**25***c* follow the method described above with regard to FIGS. **21***a* and **21***b* or FIGS. **21***a* and **21***c*. The three masks have to be exposed sequentially after aligning each mask with the photoresist.

If this pattern is next to the border of the grid as shown in FIG. **26**, then the grid boundary **180** can be part of the mask of the grid joint boundary on the left, as shown in FIG. **27**. At a minimum, the grid border **180** consists of a wide grid border for structural support, may also include patterned outside edge for packaging, interlocks and peg holes for assembly and stacking. The procedure would be to expose the photoresist **710** by masks shown in FIGS. **25***a* and **25***b* following the method described in FIGS. **21***a* and **21***b* or FIGS. **21***a* and **21***c*. The exposure of the joint boundary section **170** in FIG. **27** follows the method described in FIGS. **21***a* and **21***b* or FIGS. **21***a* and **21***c* while the exposure of the grid border section **180** in FIG. **27** follows the method described in FIG. **22**.

Grid Design Type II For Linear Motion

The exposure of the photoresist for a "tall" type II grid pattern design for linear grid motion, such as those grid patterns illustrated in FIGS. **8**, **10**, **17**, and so on, can be implemented based on the methods described in U.S. Pat. No. 5,949,850, referenced above. The grid is considered "tall" when

$$H\sin(\Phi_{max})?s,$$

where H is the height of a single layer of the grid, Φ_{max} is the maximum angle for a grid as shown in FIGS. **2** and **3**, and s is related to the thickness of the grid wall as shown in FIGS. **7**, **8**, **10** and **17**. "High" grids are not easy to expose using long sheet x-ray beams when the same grid pattern is implement from top to bottom on the grid.

As described in an earlier section, the grid shape shown in FIGS. **8**, **10**, **17**, and so on, need only be just high enough to block the primary radiation without causing undesirable exposure. Using the grid pattern shown in FIG. **10** as an example, three x-ray masks, FIGS. **28***a,* **28***b* and **28***c* can be used for the exposure. Additional x-ray masks might be required for edge joints and borders. The exposure of the photoresist for the joints and borders would be the same as for that describing FIG. **27**. The virtual "+" **210** shows the location of the central ray **63** in FIGS. **28***a,* **28***b* and **28***c*. The dashed lines **211** denote the reference line used in the exposure of the photoresist by sheet x-ray beam as described in FIGS. **21***a* and **21***b* or FIGS. **21***a* and **21***c*. The three masks have to be exposed sequentially after aligning each mask with the photoresist.

V. Packaging

The grids have to be assembled, and sealed for protection and made rigid for sturdiness, as will now be described.

1. Assembly: A layer of the grid can be made in one piece or assembled together using a number of pieces and stacking the layers using pegs, as described in U.S. Pat. No. 5,949,850, referenced above.
2. Sturdiness: The grid can be made rigid when two or more layers become physically attached after stacking to make a higher grid. A few of these methods are described below.

   The grid and pegs can be soldered together along the outer border.

   A layer of the grid, made of lead/tin, can be placed next to a layer of the grid made of a different material such as nickel. When heated, these two layers will be attached. This process can be repeated until the desired height is reached for the grid.

   A layer of the grid does not have to be electroplated using just one type of material. For example, either the top or bottom surface, or both surfaces, of a predominantly nickel grid layer can be electroplated with lead/tin next to the nickel before it is polished to the desirable height. When layers of grids made by this approach are stacked together and heated, the various layers become physically connected. This method does not coat the whole grid with solder.

Many parts of an assembled and stacked nickel grid will be fused together when the grid is brought up near the annealing temperature.

3. Framed Construction: Instead of using pegs and fixed posts, a thick and wide frame can be sued for assembly and packaging. FIG. **29** is a side view of the grid showing frame **400**. The bottom layer **401** of the grid has extra material at comers of the intersections of its walls as shown, for example, in FIGS. **8**, **10** and **17**, to provide uniform exposure during grid motion, and the other grid layers **402** do not have extra material at the corners of their wall intersections.

The frame **400** can be made by the SLIGA process as known in the art. FIG. **30** illustrates a top view of an exemplary frame **400**. The shape of the frame wall can be any design appropriate for interlocking, and the material of which the frame is made can be any suitable material, as long as it is not excessively soft. Also, the frame **400** can be made by joining two or more pieces together.

The grid is assembled by fitting grid layers **401** and **402** into the frame. If grid layer **401** is attached to the substrate but the photoresist is removed, the frame **400** can be fitted over grid layer **401**, and the grid layers **402** can then be fit into the frame. Since the frame **400** provides structural support and alignment of the openings in the grid layers **400** and **401**, the joints of the grid pieces as shown in FIG. **31** can be relaxed to straight borders **1 10** and **11 1**, and do not need to be rounded as shown in FIG. **18**, for example.

4. Sealing: To protect the assembled grid, the grid has to be covered and sealed using low atomic number materials. There are a wide variety of commercially available choices for sealing material.

Although only a few exemplary embodiments of this invention have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of this invention. Accordingly, all such modifications are intended to be included within the scope of this invention as defined in the following claims.

What is claimed is:

1. A grid, adaptable for use with electromagnetic energy emitting devices, comprising:

at least one solid metal layer, formed by electroplating, comprising:

top and bottom surfaces; and

a plurality of solid integrated walls, each extending from the top to bottom surface and having a plurality of side surfaces, the side surfaces of the solid integrated walls being arranged to define a plurality of openings extending entirely through the layer, and at least some of the walls extending at an angle other than 90° with respect to the top and bottom surfaces such that the directions in which the walls extend all converge at a point in space at a predetermined distance from the front surface of said at least one layer.

2. A grid as claimed in claim **1**, further comprising a plurality of said layers which are stacked on top of each other such that walls of the layers are substantially aligned so that the openings in the layers are substantially aligned to form openings which pass entirely through the grid.

3. A grid as claimed in claim **1**, wherein said at least one layer comprises a plurality of sections, each including a portion of the top and bottom surfaces and some of said walls, at least two of said sections being coupled together to form at least a portion of a said at least one layer.

4. A grid as claimed in claim **3**, wherein the separate sections of the grid are coupled together on a support surface.

5. A grid as claimed in claim **3**, wherein the separate sections are glued together.

6. A grid as claimed in claim **3**, wherein:

each of said plurality sections includes at least one of recesses and projections; and

certain of said projections of each of said sections are received into certain of said recesses of certain other of said sections to couple said sections together.

7. A grid as claimed in claim **2**, wherein:

when said grid comprises eight of said layers each having a height H, said grid transmits electromagnetic energy received thereby at a transmission angle **0** according to the following equation:

$$-1/(2(1+\Sigma 2^{n})H)\leqq\theta\leqq 1/(2(1+\Sigma 2^{n})H)$$

for n=0 to 3.

8. A grid as claimed in claim **2**, wherein:

each of said layers includes a metal border having alignment openings therein; and

said alignment openings of each of said layers align when said layers are stacked on top of each other.

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